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Technology Roadmapping for mission-led agile hardware development: a case study of a commercial fusion energy start-up

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ABSTRACT

Despite several decades of dedicated R&D, fusion, a potentially world-changing energy source, remains decades away from commercialisation. The majority of development thus far has been via publicly-funded programmes led by government laboratories focused on scientific research and in which commercialisation strategy and innovation play a minor role. Generally, such programmes follow a linear model of innovation in which commercial aspects are not considered until later in development. In consequence and without intention, devices not well-suited for commercial application are being pursued. In recent years, however, privately funded fusion start-ups have emerged with the goal of accelerating the commercialisation of fusion. Fusion start-ups are, by necessity, operating on a fundamentally different model of innovation: agile innovation, whereby technology is developed flexibly and iteratively towards an explicit commercial goal. Technology Roadmapping is a method that has been effective for supporting agile innovation but thus far has had limited application to mission-led hardware development. We characterise the key features of the fusion innovation approach and create a novel Technology Roadmapping process for fusion start-ups, which is developed via a case study with Tokamak Energy Ltd. The main elements of the developed process, the resulting Technology Roadmap, and its impact are presented.

1. Introduction

Harnessing the energy from nuclear fusion has long been heralded as the solution to the world's energy problems. Nuclear fusion is the process that powers the sun and the stars, in which atomic nuclei, under high pressure and high temperatures, can overcome the forces of nuclear repulsion and join to create a heavier nucleus, releasing high levels of energy in the process (Burbidge et al., 1957, Chen, 2011). On Earth, scientists are developing fusion reactors to mimic the process to produce energy from the fusion reaction for the generation of clean electricity or process heat. However, despite dedicated government-led publicly funded fusion research programmes since the 1960s, latest projections place commercialisation of fusion energy well into the second half of the 21st century. These timescales would mean that fusion will likely be too late to contribute to the current and near-future efforts to avoid serious climate change. Thus fusion is likely to be excluded from the current clean energy technology revolution to move away from a dependence on fossil fuels (Lopes-Cardozo, 2019). This paper considers an alternative pathway to fusion commercialisation, as motivated by a desire to deliver beneficial impacts to society on a shorter timescale.

The long-standing conventional view has been that the development of fusion is possible only through government-funded and government-coordinated science projects. In those programmes, the approach has been first to achieve a high degree of scientific understanding and to resolve key technical challenges. The broader challenge of commercialisation is not considered until much later in development. This approach has resulted in increasingly large, complex and expensive devices that typically take decades to construct and operate. Such devices are then intended to operate as scientific research facilities for several more decades. Fusion research and development for energy supply has thus far been based almost solely on a single technical approach: the tokamak (Ikeda, 2009, Sánchez, 2014). Tokamaks use magnetic fields to confine a plasma containing ionised isotopes of hydrogen, typically deuterium and tritium[1], and auxiliary systems to heat the plasma to high temperature (~ 100 M Kelvin). At high temperatures, the

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[1] The fusion reaction between deuterium and tritium is commonly known as DT fusion.

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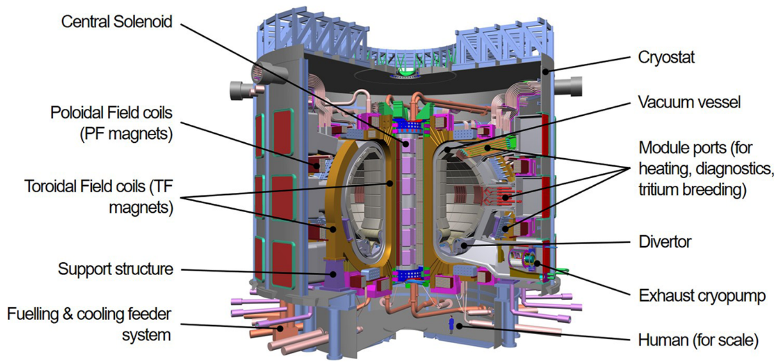

Figure 1. Schematic of the ITER tokamak with labels indicating core systems. Adapted from (ITER Organisation 2019) with permission of the ITER organisation (©iter.org).

deuterium and tritium ions fuse to make heavier elements, mainly helium, and in the process release energetic neutrons. Under the right conditions, net power from the DT fusion reaction can be achieved. However, such conditions have not yet been demonstrated, and thus achieving net power conditions are the central focus of all fusion programmes.

Tokamaks are complex devices with many systems and components, all of which are necessary to develop and harness energy from the nuclear fusion reaction. The focus on the tokamak design in the latter part of the 20th century culminated in the creation of the internationally coordinated ITER project, which will be the largest tokamak ever built with a plasma volume of about 1000 m^3, an estimated cost of about $20B by 2025, and a design-to-operation time in the order of 30 years (Clery, 2015, Locatelli, 2017). The plasma generated by ITER is expected to produce approximately ten times more power than is used to create and heat it. ITER is regarded as being a major step towards the realisation of fusion energy. Fig. 1 shows a labelled schematic of the ITER tokamak.

Delays to the ITER project, as well as the advent of new technologies and recently improved understanding of the physics of fusion plasmas suggest that alternative approaches based on smaller, simpler and cheaper devices might be possible (Costley et al., 2015, Whyte et al., 2016)[2]. This notion has stimulated the emergence of more than a dozen entrepreneur-led and privately funded enterprises, here referred to as as fusion start-ups, all of which are aiming to develop fusion on a faster timescale. Principally, such fusion start-ups are pursuing smaller and simpler devices, and some have adopted an approach based on the tokamak and thus have a well-developed physics base (see (Gryaznevich et al., 2015, Sorbom et al., 2015)). Two examples of tokamak based approaches are Tokamak Energy in the UK (Tokamak Energy Tokamak Energy Ltd Website) and Commonwealth Fusion Systems in the U.S. (Commonwealth Fusion Systems Website 2019). Examples of start-ups pursuing alternative novel concepts are First Light Fusion in the UK (First Light Fusion First Light Fusion Website) and General Fusion in Canada (General Fusion Website: generalfusion.com 2019). All employ novel and disruptive technologies on critical, high leverage components, for example, high temperature superconducting (HTS) magnets for tokamaks, and low-cost plasma drivers and lasers for non-tokamak concepts (see (Wurden et al., 2016)).

Despite distinct differences in technical approach, all fusion start-ups share a common aim: to accelerate the development of fusion via less complex, smaller, cheaper devices, with the explicit goal of commercialisation. All fusion start-ups are backed by investors who want to see rapid development towards a commercial product as well as a return on investment. As such, the fundamental difference between public programmes and fusion start-ups is not just in the technical approach to fusion – that is, the reactor concept – but in the development approach or, more specifically, the approach to innovation[3]. Thus far, public fusion programmes have mainly followed a linear model of innovation in which science and technology aspects are the focus, while aspects relating to commercialisation play only a minor role, particularly in the early development phases. In contrast, fusion start-ups are following a fundamentally different model of innovation: primarily agile innovation, with some elements of lean innovation. Agile innovation focuses, in particular, on building, testing and learning iteratively on rapid cycles, which facilitates accelerated development towards an explicit commercial goal (Ries, 2011). It is an approach used in the space exploration sector, for example, by SpaceX (Rigby et al., 2018). Lean innovation evolved from manufacturing with a focus on minimising waste in terms of time, resource and effort.

Fusion innovation has not yet been significantly explored or characterised in the existing literature. Accordingly, by first exploring the core principles that underpin the innovation approach of publicly-funded government-led fusion programmes, this paper characterises the current paradigm shift towards fusion start-ups, and draws parallels with the space exploration sector. However, innovation is a dynamic process that does not occur naturally. It involves the continuous review and iteration of the medium and long-term strategies to ensure that technology development in the near-term is in the direction of commercial interest (Fitzgerald et al., 2011, Pisano, 2015). Fusion start-ups require tools and methods to navigate the commercialisation process. One tool commonly applied to support innovation management, and agile innovation, in particular, is Technology Roadmapping. Technology Roadmapping is a process that provides an overview of key activities required to develop specific technologies or products for an organisation or company. It facilitates the creation of an innovation strategy through the alignment of technology or product development with an organisation's capabilities, its commercial goals and market needs (Phaal et al., 2010, International Energy Agency 2014, Albright and Kappel, 2003, Kostoff and Schaller, 2001). Technology Roadmapping has been adapted to a wide range of contexts, including to support agile innovation. However, thus far, it has had limited application to problems involving hardware development that typically require long timescales and significant up-front investment.

We have developed a novel Technology Roadmapping process

[2] The compact, high-field tokamak approach was originally conceived by Bruno Coppi and others in the early 1980s and proposed as an alternative to ITER. A compact high field device utilising copper toroidal field coils (IGNITOR) is still under active development (Coppi et al., 2015). If Ignitor had been developed to prove ignition in a tokamak it would have added great impetus to fusion development, and perhaps accelerated the emergence of fusion start-ups that is seen today.

[3] Herein we take the definition of innovation to be “invention plus exploitation”.

tailored for such applications. We have used it in a case study with Tokamak Energy Ltd, a privately funded fusion start-up based in the UK aiming to realise commercial fusion via the spherical tokamak and HTS magnets (Sykes et al., 2018, Costley, 2019, Windridge, 2019). The Technology Roadmapping process, as well as the resulting roadmap and the impact on how it supports development and innovation, are derived from the application at Tokamak Energy. The description of the process and its outputs provides a framework for other fusion start-ups or similarly complex or challenging hardware-focused technology endeavours. Our work represents a new application of roadmapping to agile organisations pursuing mission-led hardware development, especially start-ups. In this paper, we present the process, the results and applications of our work, and recommendations for future development in this area.

The structure of the paper is as follows: In section 2, the approach to innovation for the public fusion programme and hence the fundamental differences of the fusion start-up approach are outlined. A brief overview of Technology Roadmapping, with a focus on its potential usefulness to the fusion start-up context, is provided in section 3. The steps to develop a first-pass roadmap are described in section 4. The process to develop the roadmap further is described in section 5, with specific emphasis on the application at Tokamak Energy as the case study. Section 6 details the outcomes and impact of the roadmapping at Tokamak Energy. In section 7, strengthening the roadmap by adding a commercial layer to the roadmap using established analysis tools is discussed. The generalisability of the process and possible application beyond the single case study, including to other fields, is discussed in section 8. The paper is summarised in Section 9.

2. Fusion start-ups: A paradigm shift

2.1. Public fusion programmes and the linear model of innovation

The early years of fusion development were underpinned by a desire to shift an early Cold War nuclear arms race into something that instead resembled social value. Famously, the development of ZETA (Zero Energy Thermonuclear Assembly), an early non-tokamak fusion reactor, at Harwell, UK was based on previous experiments from the nuclear weapons laboratory at Aldermaston (Braams and Stott, 2002, Carruthers, 1988). ZETA, despite some important scientific successes, is remembered for erroneous mass media reports that evidence of fusion had been seen. It later became clear, in line with US and Soviet experiments, that fusion had not occurred. ZETA caused embarrassment for the British fusion community, but nevertheless the rapid shift in focus towards civil fusion programmes continued in many countries including the UK. These grew in strength and gradually assumed remarkable prominence in international relations (ITER Organisation, 2018). Several decades later in 1985, and after considerable success with tokamaks, a crucial step in the development of fusion was reached. An agreement was made between the leader of the Soviet Union, Mikhail Gorbachev, and President of the United States of America, Ronald Reagan, for the joint development of a large scale fusion device; the International Thermonuclear Experimental Reactor (now known only as ITER) (ITER Organisation The ITER Story). The cost and scale of the ITER project, alongside its political importance, brought about a shift in the organisational culture for fusion scientists and engineers. For such projects, technical proposals are simulated and tested before being implemented into the design and to proceed with greater technical certainty requires time and delays can accumulate. It is perhaps therefore unsurprising that government-led publicly funded fusion efforts spend enormous amounts of time and money rigorously planning every step of the way forward to ensure the best chance of success. It seems that such publicly funded fusion programmes may be incapable of agile innovation; rather, they generally follow the more cautious linear model of innovation.

The *linear* model of innovation, also referred to as the *pipeline* model, places science and technology as the main drivers of innovation, and represents an approach to innovation that is "technology-push", where the technology is developed from scientific research and then subsequently "pushed" into the market (Bush, 1945, Bonvillian and Weiss, 2015, Kline and Rosenberg, 1986). It typically underpins government-led projects, by guiding the early stages of innovation that carry a high cost and technological risk before industry takes over to take the technology to market (Fitzgerald et al., 2011, Bush, 1945, Bonvillian and Weiss, 2015).

A variation of the pipeline model is the *extended pipeline* model. The stage of innovation between R&D and commercial market is commonly known as the "*valley of death*". The *extended pipeline* model is typically associated with the development of radical technology as it sees government involvement continue to the latter stages of the innovation process. In effect, therefore, it supports the maturity of the technology through the *valley of death,* reducing the risk of technological failure between a prototype and a first commercial product (Lopes-Cardozo, 2019, Bonvillian and Weiss, 2015, Rogers, 2003, Branscomb and Auerswald, 2002).

Both variants of the linear model, principally by way of government-led defence R&D, were behind some of the great successes of the 20th century, for example in computing, space, biotechnology, and, of particular relevance here, nuclear fission technology (Bonvillian and Weiss, 2015, Ruttan, 2006). At the dawn of the atomic age, the only model of innovation for technology development was the linear model, and because of the scale, cost, and radioactive nature of the experimental fission devices, government laboratories undertook the development via this model. Harnessing energy from the fission reaction is relatively straightforward compared to fusion. Once it was demonstrated that power production was feasible, private companies quickly emerged to take on the development and the commercialisation of fission-based nuclear power technology. Accordingly, government laboratories subsequently moved to support the nuclear industry by supporting R&D. That has not been the case for fusion. Fusion represents a more significant technical challenge which must first be overcome in order to show its commercial potential. It is taking much longer to develop the technology past the early stage, and fusion has remained predominantly in the domain of government laboratories, and somewhat held back by linear innovation. Accordingly, over half a century after the commercialisation of fission, the development of fusion continued on the linear model, which is evident through dedicated efforts by multiple nations to design and commission large-scale next-step DEMO devices after ITER. These are not expected to operate until at least 2050. In the context of the linear innovation model, DEMO reactors are prototypes intended to be the final step before a first commercial fusion device, but – importantly – is not a commercial device. Instead, the expectation is that industry will take over after DEMO, following the convention of the linear model. However, the recent emergence of significant privately funded fusion start-ups is disrupting this paradigm.

As a government-led project that has consumed a substantial portion of global fusion R&D resource over the past two decades, ITER has limited the development of alternative approaches and effectively "*placed all of fusion's eggs in one basket*" (Walker and Haines, 1997). The success of projects such as ITER is paramount. Incentives and pressures lead to an avoidance of risk via, for example, only permitting the use of mature technologies. Risk minimization and avoidance leads to more rigorous designing and testing, which in turn creates delays and cost overruns. In extremis, this cycle becomes the normal to drive an approach that is dominated by the notion that *"failure is not an option"*

(McCurdy, 2001). For ITER, the focus on rigorous planning and testing to reduce risk before building has resulted in increased cost and delays (Lopes-Cardozo, 2019). Beyond ITER, for publicly funded government-led fusion programmes in general, this has led to the pursuance of devices that are not well suited for commercial application and unlikely to be developed fast enough to contribute to the energy mix until at least the latter part of the 21st century (Lopes-Cardozo, 2019). Similar problems have previously manifested in other large-scale publicly-funded and government-led projects such as several of NASA's space programmes (see (McCurdy, 2001, Board of Space Studies: National Academy of Sciences Engineering and Medicine 2017)).

Weaknesses of the linear model of innovation include a lack of feedback and learning, which will be detailed subsequently in section 2.2. However, one particular weakness is the minimal emphasis on commercial requirements as a driver for development in the near and mid-term stages (Bonvillian and Weiss, 2015). Thus, development on the linear model commonly yields products that may be technologically advanced, but which may not be commercially viable. A typical example of this is the development of Concorde, which, while arguably an engineering masterpiece, was a significant commercial failure (Kline and Rosenberg, 1986)[4]. Fusion energy has consistently been conveyed as a technology with the potential to be superior to any competing energy technology. Beyond the fact that this promise is yet to be demonstrated in reality, technological sophistication is not intrinsically valued in the market unless it offers superior performance with only a modest increase in cost (Kline and Rosenberg, 1986, Walker and Haines, 1997). In short, the slow progress and high development cost of large government-led fusion projects are consequences of the perceived need to reduce risk as well as adherence to a linear model of innovation.

As early as 1981, it was suggested that fusion based on large tokamaks would not result in commercial success due to scale and complexity, and thus cost (Carruthers, 1981). This perspective was echoed and further developed over the subsequent decades by Kulcinski and Santarius (Kulcinski and Santarius, 1998), the Electric Power Research Institute (Kaslow et al., 1994), and Walker and Haines (Walker and Haines, 1997). These authors advocated that commercialisation could be emphasised through the pursuit of simpler (but not necessarily smaller) and low-cost experimental reactors. This approach would also motivate developers to explore routes to commercialisation that were not solely focused on electricity generation. Despite the rationale for such an approach, which did not dispute the scientific basis of large tokamaks but rather the approach to development (and intrinsically the innovation approach), the direction of ITER has remained unchanged, and has been firmly at the centre of focus of the international fusion programme for the past two decades. However, the emergence of privately funded fusion start-ups is beginning to disrupt this status quo and create a paradigm shift.

2.2. Innovation in fusion start-ups and parallels with the space exploration sector

In contrast to public fusion programmes, private fusion start-ups are backed by investors who naturally want to see rapid development towards a commercial product as well as a return on investment. Limited resources, and in some cases an incomplete understanding of the core science and only partially developed technology, requires start-ups and their backers to be prepared to accept higher risk. Private sector start-ups have an attitude to risk not based on strategies of minimization and avoidance, but rather the focus is on a need to maintain forward momentum, to expect problems and to learn from them. This strategy works well when faced with the difficulties that are inevitable in highly complex and tightly coupled systems with a focus on hardware development. With this higher acceptance of risk, and with smaller and simpler machines, fusion start-ups can develop technology at higher speed and lower cost, and thus can improve the chance of successful innovation (McCurdy, 2001). By rapidly learning and adapting from failures, fusion start-ups expect to make significant progress measured in the order of years rather than decades. Accordingly, the underlying philosophy of fusion start-ups to iterate rapidly, and to proceed with risk and to learn from failure, indicates that they operate on a fundamentally different model of innovation. Ostensibly, a “paradigm shift” towards fusion start-ups developing via this new model is underway[5].

It is instructive to draw a comparison between the fledgeling fusion paradigm shift and the more established shift of start-ups seeking to commercialise space exploration and travel. The parallels in the innovation approach are clear; fusion start-ups are to publicly-funded government-led fusion programmes as SpaceX, Blue Origin, and Virgin Galactic are to governmental or intergovernmental space agencies such as NASA or the ESA. Both fusion start-ups and space sector start-ups are funded by private capital and are disrupting a sector previously occupied only by national programmes. Where NASA's mission is to advance the boundaries of technology and science, space start-ups (SpaceX is perhaps the bestknown example) have been founded to commercialise space travel. Similarly, where ITER is an experimental project that will help pave the way for future commercial development (via a next-step DEMO reactor), fusion start-ups are focused on exploiting the technology's commercial potential. Both sectors require significant upfront investments for the development of expensive and complex hardware, for which the development unavoidably has high front-end risk. However, both also come with the promise of realising a world-changing innovation. SpaceX has actively demonstrated that by learning rapidly from failure, through short innovation cycles, they minimise the time required to build, test and learn, hence accelerating overall development. SpaceX is farther progressed in its mission to commercialise space travel than other similar technology start-ups are in their respective missions and is thus inspiring others to adopt its approach. Consequentially, the SpaceX model is now being suggested as a foundation for the development of advanced nuclear fission power, for example, see (Bowen, 2019, Abdalla, 2019)[6].

Throughout the history of technological development, it has always been the first demonstration – for example, the first controlled powered flight or the first controlled fission reaction – that was, often in hindsihght, considered as the “*breakthrough*” point. In contrast, controlled fusion has been achieved in the JET and TFTR tokamaks but not yet at a level where net fusion power has been achieved (see (Keilhacker et al., 1999, Hawryluk et al., 1998)). Thus, the critical breakthrough scientific step towards the realisation of fusion has yet to be achieved, namely: controlled net fusion power[7]. A key distinction is that while SpaceX is confident that space travel has been demonstrated to be technically possible, there is uncertainty around the technical feasibility of achieving controlled fusion for fusion start-ups. It is, therefore, instructive to draw a comparison with the Wright brothers as a similar mission-led endeavour which was pursued with great technical

[4] We use ‘arguable’ to describe the engineering excellence of Concorde as serious safety weaknesses of the aircraft were revealed by the tragic crash of an Air France Concorde near Paris on the 25th of July 2000, which highlights that engineering and commercial success are not always easily decoupled in the development of hardware.

[5] We take the definition of paradigm shift from (Bonvillian and Weiss, 2015) and (Kuhn, 1962).

[6] In particular, Abdalla et al. have developed this theme further by providing a view of how the SpaceX innovation approach could be adopted by organisations in the nuclear fission industry (Abdalla, 2019).

[7] While fusion-based thermonuclear weaponry was developed and demonstrated in the 1950s, and this was indeed important for the demonstration of fusion physics, we do not regard that step as being as the fusion energy breakthrough outlined above. This is because the ‘hydrogen bomb’ explosions were uncontrolled once initiated.

uncertainty[8]. Fusion start-ups are aiming to commercialise fusion on an accelerated timescale, but before they can start on that development, they have to demonstrate fusion's breakthrough moment. Rather than comparing the current position of fusion start-ups to SpaceX, it is more appropriate to compare it to the position of NASA in the 1960s before it was successful in landing humans on the moon or to the Wright brothers in the early 1900s before anybody had demonstrated controlled flight. Such missions required technological innovation in an unproven venture. However, the approaches of NASA and ITER have been similar because both faced major technical challenges in which there were many unknowns and risks, yet neither was primarily motivated by commercialisation. Therefore, combining aspects of the commercially-driven SpaceX approach to innovation with the science-driven approach of historical innovation, i.e. with and without explicit commercial motivation respectively, we begin to converge on the principles that characterise the innovation approach, and the innovation model, adopted by fusion start-ups.

2.3. Combining agile with lean: a model of innovation for fusion start-ups

An innovation model for fusion start-ups must encompass both the technical and commercial aspects of development, i.e. both the "technology-push" and "market-pull" drivers, and this is the central difference to public fusion programmes. The *innovation organisation* model is one such model that accounts for both (Bonvillian and Weiss, 2015). The *innovation organisation* model includes the linear (pipeline) and extended pipeline model, as previously introduced, as well as the induced innovation model and the chainlink model (Bonvillian and Weiss, 2015, Kline and Rosenberg, 1986, Ruttan, 2000)[9]. For fusion start-ups, however, an innovation model must also be suitable for iterative hardware-based technology development, and must emphasise an underpinning philosophy to fail and learn quickly through building and testing. Such an approach aligns with the well-understood principles of agile development and lean production. However, neither agile nor lean is a direct fit. Before characterising how fusion start-ups encompass aspects of both agile and lean, we briefly outline the key aspects of these two methods of innovation.

Agile was originally developed to facilitate rapid innovation in software (see (Beck et al., 2001)), but since its inception, it has been adapted to a variety of other sectors, hence *agile innovation* (Rigby et al., 2018, Beck et al., 2001, Abrahamsson et al., 2002, Hannola et al., 2013, Tura et al., 2017). The fundamental principle of agile innovation is to develop a technology or product by iterating fast, failing fast and - consequently - learning fast, which allows for adaptation to emergent risks and opportunities due to the short time over which the iteration occurs (Ries, 2011, Miller and Lee, 2001). Agile innovation is based on the concept of working towards a *minimum viable product* (MVP); a version of a product that has the main features needed to demonstrate success, but which can be built with minimal effort and cost. Importantly, therefore, an MVP does not represent a final product and thus must be designed with foresight and with scope for necessary improvements in mind (Ries, 2011). Agile innovation underpins some of the successes of the companies detailed in section 2.2, like SpaceX, in which the rapid building and testing of prototypes is central to the development process. Accordingly, SpaceX presents a real-world application of agile innovation for hardware development[10] (Rigby et al., 2018).

The agile innovation approach dictates that prototypes are relatively simple and amenable to relatively short development cycle times. It is here that we find the major difference between fusion start-ups and the current public fusion programmes. The long development times of large government projects such as ITER and DEMO limit the use of the latest technologies and new engineering methods, which thus limits learning and agility. Developing technology in an agile manner, i.e. through rapid iterations, permits learning while also affording the possibility of integrating novel technologies at the next iteration or by allowing for changes, for example in the market and policy environment, to influence development. Such a development approach reflects a broader trend seen across multiple sectors over recent decades, whereby large R&D-intensive companies have become aware that internal R&D does not always succeed in producing commercially attractive inventions. In response, many have adopted an approach to R&D that encompasses the concept of open innovation[11] (Chesbrough and Crowther, 2006). Open innovation fits with agile since it is defined as the "*combining [of] internal and external ideas as well as internal and external paths to market to advance the development of new technologies*" (Chesbrough, 2003). In the context of fusion, large and complex devices developed over long timescales suffer from technology redundancy, whereby technology becomes out of date and thereby the mission cannot adapt to emergent risks and opportunities. Accordingly, the public fusion programme represents an approach that is not agile and also one which operates largely as a closed innovation system.

Closely related to the agile approach is lean. Where agile originated in software, lean evolved from manufacturing from the need to minimise waste in terms of time, resource and effort. The Toyota Production System characterised lean production in the early 1980s (see (Liker, 2004)). However, its origins are traced back to Deming's process of "plan-do-check-act" for continuous product improvement in 1950 (Neave, 1987). Lean production emphasises the reporting of failure in order to learn from it. The approach has more recently been extended from production methods to programme management and development, and lean innovation as an approach has been utilised in multiple contexts (see (Sehested and Sonnenberg, 2010) and Fig. 2). Lean innovation operates on many similar principles to agile, for example, in the way that it promotes *learning through discovery*. Accordingly, agile and lean innovation have developed in parallel, and they are often perceived as synonymous (see (Ries, 2011)). However, while the two approaches have different origins, they are complementary and intertwined in practice, as shown by the illustration in Fig. 2.

Agile and lean, adapted from (Ries, 2011, Beck et al., 2001, Abrahamsson et al., 2002, Liker, 2004, Neave, 1987, Poppendieck and Poppendieck, 2003), are compared and contrasted with the innovation approach of fusion start-ups and public fusion programmes in Table 1. While both are focused on mission-led hardware development, it is evident from the comparison that fusion start-ups operate on agile and lean principles and publicly-funded government-led programmes are more linear and closed in the approach to innovation[12].

One aspect of both agile and lean innovation that is fundamental for

[8] Whilst our analogy of the Wright brothers is set in the context of innovation, others in the fusion community have made a similar comparison, including The American Security Project, scientists at Sandia National Laboratories (Sinars et al., 2016) and at Massachusetts Institute of Technology (Private communication with Dennis Whyte at Massachusetts Institute of Technology, November 2017), as well as entrepreneurs and scientists at both Commonwealth Fusion Systems and Tokamak Energy Ltd.

[9] The induced innovation model dictates that market demand drives technology development (Bonvillian and Weiss, 2015, Ruttan, 2000). The chainlink model accounts for both technology-push and market-pull by exploring market needs whilst also accounting for explicit feedback loops such that all stages of the innovation process (research, design, production, and market) drive one another (Kline and Rosenberg, 1986).

[10] Also refer to NASA's "Pathfinder" mission, which adhered to agile and lean innovation principles, see (Muirhead, 1997) and (Pearson, 2020).

[11] Open innovation is founded upon the notion that valuable ideas from outside of an organisation that influence the internal activity of an organisation should be identified and determined, and vice-versa (Chesbrough, 2003).

[12] Where the table provides a description of the fusion start-up approach, it can also be perceived as a prescription or guide for fusion start-ups seeking increased agility and leanness in their development approach.

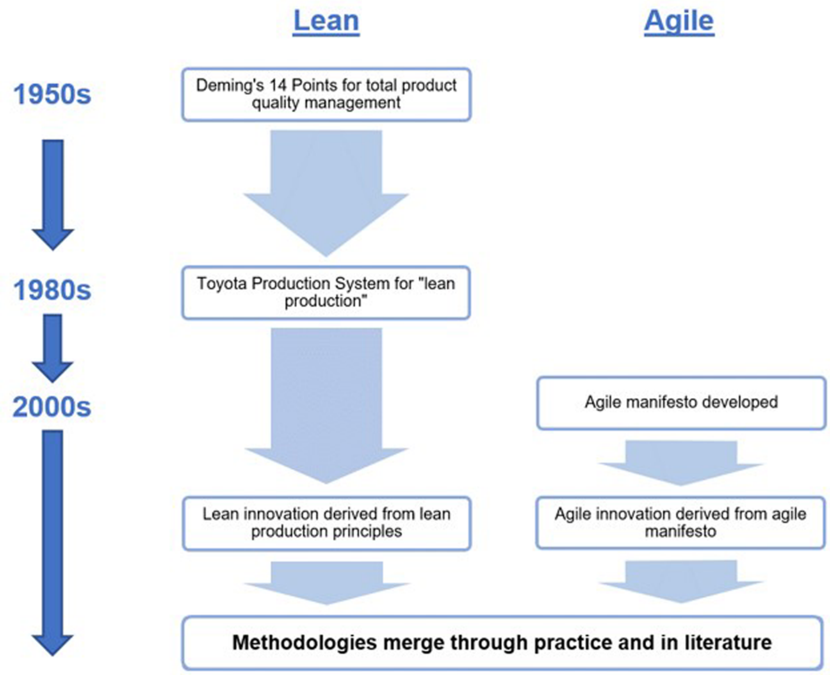

Figure 2. The co-evolution of agile and lean innovation

fusion start-ups is the approach to technology development. For agile, it is the process of "build-measure-learn" towards an MVP, and for lean, it is the process of "plan-do-check-act" for continuous product improvement (Ries, 2011, Poppendieck and Poppendieck, 2003, Agan, 2014). While the foundation of the agile approach is in the ability to iterate quickly at low cost, for the lean approach it is less about speed and more about enhancing efficiency and reducing waste. Therefore, it is more apposite to employ the MVP concept from agile to help understand the innovation approach for fusion start-ups. The equivalent MVP for fusion start-ups is a device that is capable of demonstrating the commercial viability of fusion. The fusion plasma in such a device must controllably produce significantly more energy than is supplied to it and must demonstrate that it can be scaled to a commercial device. For a hardware-based technology development mission such as fusion, whereby physical devices must be built, applying agile principles is not straightforward, and thus an adapted approach is required. It is appropriate, therefore, to show steps towards a fusion MVP as *minimum viable demonstrations* (MVDs). MVDs can be designed as targets to demonstrate technology performance and to develop solutions to non-technical problems that must be solved in parallel, e.g. materials supply chains, regulation, infrastructure etc. The most important MVD on the path to an MVP is the demonstration of first net power gain. It is expected that the fusion start-up (or start-ups) first to realise this MVD, defined here as the *breakthrough MVD*, will see a surge of interest and investment akin to that seen during the pioneer era of aviation sparked by the first demonstration of controlled flight (Penrose, 1967). Importantly, the *breakthrough MVD* must exist on a path that is scalable to an MVP and subsequently to commercialisation, while simultaneously being a goal that can be achieved as simply and as fast as possible (Ries, 2011). Other MVDs can be identified as necessary to show the advancement of critical technical issues for the realisation of the MVP. Thus together, MVDs show overall progression towards the commercial realisation of fusion. Fusion start-ups must therefore determine the specific requirements for MVDs, and most importantly for a *breakthrough MVD*, to plot progression to the realisation of an MVP. By being aware of the pathway to commercialisation, it is possible to build an understanding of what is required to address future challenges, and to then plot the desired progression through those challenges.

2.4. Plotting a route to commercial fusion

Technology-intensive industries evolve and develop through the different phases of innovation. The S-T-A-M model of industrial emergence, shown in Fig. 3, plots the progression through phases from science (S), to technology (T), to application (A), and then to market (M)[13]. The phases of the S-T-A-M model are thus broadly analogous to the innovation process. Accordingly, the transitions – explicitly denoted by hyphens for emphasis – can be considered as key demonstration points, which indicate the start of the next stage of the innovation process. Plotting the trajectory of an industry or organisation, the S-T-A-M model allows the key demonstration points to be outlined to enable practical goals to be established. Importantly, however, while the model appears as a linear progression, it must be viewed with the understanding that, as with all systems innovation models, the process is dynamic (Phaal et al., 2011).

If the trajectory of fusion development is plotted in the S-T-A-M model, then the science-technology (S-T) transition marks the demonstration of net power gain; the point at which the breakthrough MVD is achieved. Referring to Fig. 4, for the public fusion programmes, the breakthrough MVD, and thus the device to traverse the S-T transition is ITER. The demonstration of useful energy production from a prototypical fusion reactor is a principal goal for the multiple DEMO projects under consideration by various ITER members. DEMO, therefore, represents the device that traverses the technology-application (T-A) and is thus fusion's MVP. After that, an as-yet-unspecified first of a kind (FOAK) commercial fusion reactor would demonstrate the capability to overcome the application-market (A-M) transition. While public fusion programmes and fusion start-ups are mainly focused on the first of these transitions – the demonstration of net power gain – the S-T-A-M model provides a clear idea of the steps to be taken on the route beyond this point. It also provides the perspective that if commercialisation is the

[13] The industrial emergence model can be further delineated into "S-T-A-M" and "s-t-a-m" models (upper and lower case) to indicate the emergence of an industry and the emergence of a single organisation, respectively (Phaal et al., 2011). In this paper, for simplicity, we refer to this only as the S-T-A-M model to describe the overall emergence of fusion towards commercialisation.

Table 1
The main characteristics of agile and lean innovation models compared with the approaches used by the government-led public fusion programmes and fusion start-ups (as organisations focused on mission-led hardware development)

	Agile approach (Ries, 2011, Beck et al., 2001, Abrahamsson et al., 2002)	Lean approach (Liker, 2004, Neave, 1987, Poppendieck and Poppendieck, 2003)	Publicly-fusion government-led fusion programme approach	Fusion start-up approach
Design	Keep it simple, minimise the amount of work done by avoiding unnecessary activities. It is easier to add features to a simple product or process than it is to remove features from a complex product or process.	Eliminate “waste”, where waste is characterised as anything that does not add value (including time spent on unnecessary activities).	Engineering design activity begins after a thorough technical understanding has been developed through comprehensive R&D. Long timescales, high cost and complex design (e.g. ITER) are acceptable as long as risk is low and knowledge gained is high.	Limited resource and time forces progress without full technical know-how or understanding. Focus on simple design to ensure rapid development. Risk is acceptable and necessary to progress and to learn.
Development	Develop a working product and iterate (from which to learn). Reflect on how to improve the product; adjust and repeat. Mistakes provide valuable learning.	Amplify learning by making development an opportunity for discovery through the process of “plan-do-check-act”.	Develop key hardware to an advanced state before commencing with construction. Lengthy periods between the inception of idea and building and testing results in slower progress.	Demonstrate through building and testing, even in the face of uncertainty (e.g. unknown physics and uncertain technology performance). Avoid development not relevant to the primary mission.
Changing requirements	The best designs come from continuous iteration not from early, rigid plans. Embrace changing requirements, even late in development.	Avoid locking in on decisions until unknowns are known but make late decisions in conditions of uncertainty; build a culture that can embrace change.	Detailed design and construction generally cannot proceed until results of previous experiments are known. Late changes in design acceptable if there is a clear benefit but will cause a delay. Extensive documentation and rationale for change required.	Fast iterations and short periods between testing allow novel technology ideas to be integrated at the next stage of development. Late changes are acceptable, but not if they create delays or cost overruns.
Product	Satisfy the customer (or end-user) by quickly delivering a product that is imperfect (MVP), but which will benefit from continuous development and improvement over time based on customer feedback.	Focus on delivery to the customer as fast as possible – high speed results in rapid feedback and forces decisions. Reduce variation in standard production and processes.	Testing should provide results for the next stage, but technology redundancy (technology becoming out of date) is a risk. Cost is high, so adjacent supporting programmes are focused on ensuring the success of the primary mission rather than exploring alternative (and disruptive) technologies.	Building devices quickly can demonstrate capability and intent to stakeholders (investors, scientists and the public). Early routes to market continually explored due to explicit focus on a commercial exit strategy and achieving a return on investment.
People	Build projects around people. Innovation occurs from human interaction and self-organised teams guided by a clear vision.	Build empowered development teams with authority to make decisions, under guidance rather than control from leaders. No one understands a product or technology more than the people who work on it.	Typically involves several large organisations with many scientists and engineers, in some cases sited across the world. Coordination and organizational aspects are necessarily regimented, which makes management and team cohesion challenging.	Small groups of scientists and engineers work with greater autonomy and with a license to explore and learn, guided by a vision and led by creative business leaders (entrepreneurs).

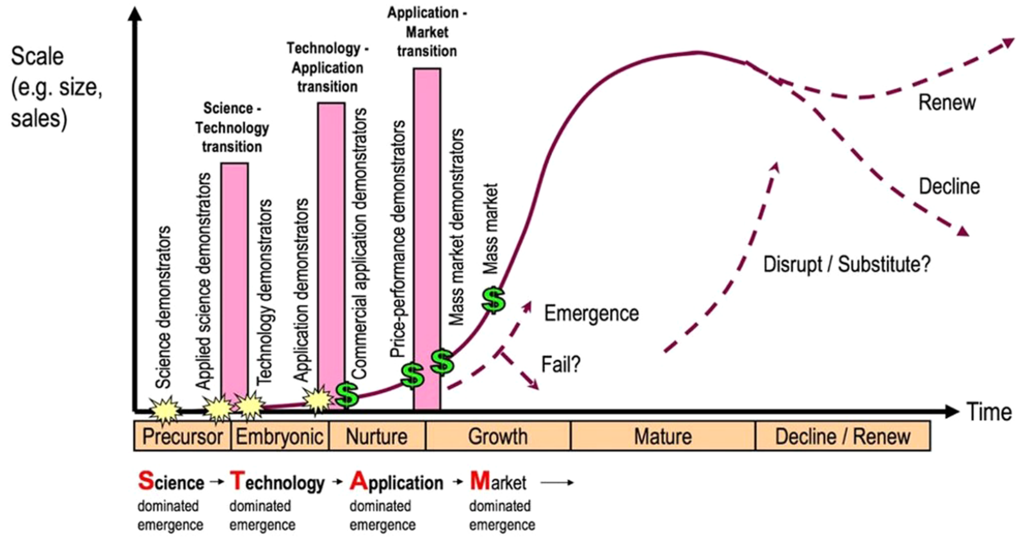

Figure 3. The S-T-A-M model of industrial emergence showing the pathway from scientific discovery to commercial realisation. Reproduced from (Phaal et al., 2011) with permission of the author (Robert Phaal) and the University of Cambridge.

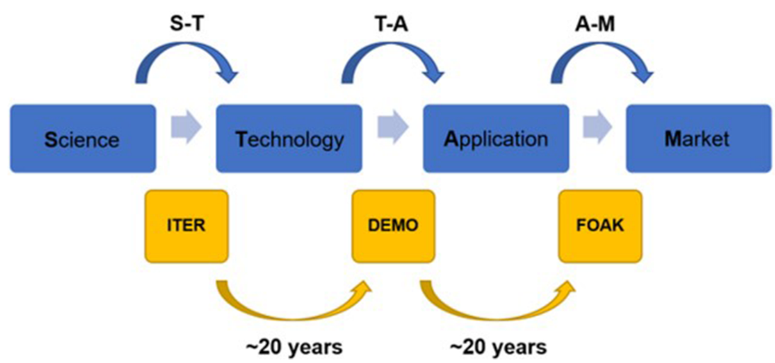

Figure 4. The public fusion programme in the context of the S-T-A-M model of industrial emergence.

goal, then it should be explicitly considered during all phases of a process that follows a dynamic – not a linear – progression.

Further, it is essential to note that both government-funded and private fusion efforts are currently in the "science" phase. Different technical approaches to fusion are ostensibly at very different levels of maturity, with tokamaks being the most advanced (Clery, 2019). The public fusion programme is expected to pass the S-T transition of demonstrating net power gain via ITER around, or shortly after, 2035. However, the subsequent T-A transition is not expected by DEMO until sometime beyond 2050. A first commercial prototype to overcome the transition to market will come at a later, as yet unknown, date. The periods between each phase of development shown in the S-T-A-M model are thus around 20 years. As a result, the realisation of commercial fusion via public fusion programmes will not occur until around 2070 or later and, on the current trajectories, will be delivered via large, complex, and expensive tokamak reactors. In contrast, fusion start-ups aim to follow a path that leads to commercial fusion using relatively small devices. They are, therefore, more capable of dynamically adjusting the mission to ensure that some form of commercialisation can occur in a shorter time. Thus, with a development approach to build fast, learn fast, and, in some cases, to fail fast by virtue of their higher acceptance of risk, fusion start-ups aim to accelerate the fusion commercialisation process.

While fusion start-ups are focused on pursuing concepts that could realise commercial fusion energy sooner, owing to the infancy of the technology, as with government-led programmes, they are still focused most closely on the early stages of the innovation process, i.e. on technology R&D. This is typical of early-stage technology start-ups, see (Liker, 2004), which tend to focus on the next deliverable rather than long-term goals. As a result, the latter stages of the innovation process, e.g. the identification of markets for the technology under development and consequent angling of the technology towards those markets, are less well developed (Kostoff and Schaller, 2001), (Liker, 2004), (Garcia and Bray, 1997). Innovation management methods permit the development of an innovation strategy that runs in parallel with the early R&D stages, to enhance the chances of innovation success (see (Pisano, 2015, Teece, 2010)). A variety of processes and tools are available to support organisations in the management of innovation. One such method is Technology Roadmapping, which enables the different elements in the programme to be clarified and managed, their interdependences to be delineated, and the dynamic adjustment of the programme to occur.

3. Technology Roadmapping

Methodologies for long-term planning, such as System Dynamics, Scenario Planning and Technology Roadmapping have been widely adopted to help governments, organisations and companies develop a strategy to achieve long-term goals (Gordon, 1992, Porter et al., 2004, Amer and Daim, 2010). Such methods necessarily take a high-level, overview approach by determining the most effective near- and mid-term activities that will deliver long-term goals, asking "where are we now, where do we want to be, and how do we get there?" (Phaal et al., 2001). Technology Roadmapping, hereafter simply referred to as

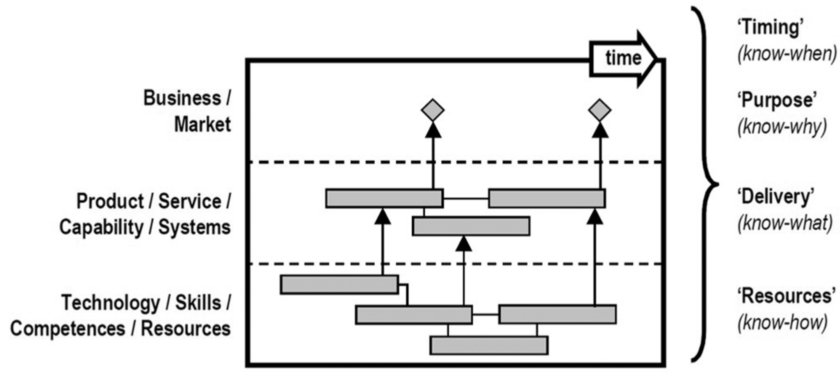

Figure 5. Typical Technology Roadmap Structure, including links to four of the 6 Ws (shown as "know-when", "know-why", "know-what", and "know-how"). Reproduced from (Phaal et al., 2001) with permission of the author (Robert Phaal) and the University of Cambridge.

roadmapping, is one such method that is particularly well suited to technology development projects, such as fusion, due to its adaptability and function to consider both technical and commercial aspects of development simultaneously, and the interactions between these elements (Albright and Kappel, 2003, Kostoff and Schaller, 2001, Phaal et al., 2001, Garcia and Bray, 1997).

The product of roadmapping is a Technology Roadmap, hereafter simply referred to as a roadmap. A roadmap is a multi-layered time-based chart on which the evolution of a particular industry, market, product or technology is plotted (Phaal et al., 2010). Roadmaps address the "*why*", "*what*", "*when*", "*who*", "*where*" and "*how*", colloquially known as the "6 Ws", which are used to guide scientific enquiry (Sharp, 2002, Kerr et al., 2013, Kappel, 2001, Phaal, 2004). The time function in a roadmap addresses "*when*", while the "*why*", "*what*" and "*how*" are typically shown as layers. The "*who*" and "*where*" are embedded in the details of a roadmap itself. The basic structure of a roadmap, including links to the 6 Ws, is shown in Fig. 5.

Both the process of creating a roadmap, i.e. roadmapping, and a roadmap itself have several useful functions. Roadmapping is carried out by individuals, typically from different functions of an organisation, who work together collectively to develop ideas and strategies towards a common goal (Phaal et al., 2010, Phaal, 2004, Zurcher and Kostoff, 1997). A roadmap, on the other hand, shows the steps an organisation needs to take to achieve its stated outcomes and goals, thereby facilitating the development of strategy (Phaal et al., 2010, International Energy Agency 2014, Winebrake, 2004). A roadmap serves as a visual tool to facilitate the identification of potential challenges, opportunities and risks on the intended future path that may affect the chosen strategy (Phaal et al., 2010, Garcia and Bray, 1997). Even though the future is uncertain and cannot be predicted with high accuracy, it is possible to plan for the identified path (or paths) as they are currently envisaged. Roadmapping typically starts with a planning stage that defines the vision and goals for the application, as well as the scope of the activity (Phaal et al., 2010, International Energy Agency 2014, Winebrake, 2004, Phaal et al., 2001). By defining a vision at the outset, and by understanding the current position in relation to that vision, the potential forward-path – or paths – can be plotted. After that, appropriate near-term decisions can be made, and resources allocated, based on the identified needs of the path, i.e. a strategy can be developed (Phaal et al., 2001).

Companies or organisations engaged in complex technology development inevitably operate in a changing environment where external developments beyond their control occur and potentially influence the intended future path and even the long-term goal(s). There will also inevitably be discoveries, both positive and negative, that impact internal activities and may affect the long-term goal(s) and the planned forward path. To be effective, a roadmap must be updated to take such developments into account. The time interval between updates will depend on the timescale of changes in the external and internal factors. Such updates are carried out by continuously iterating a roadmap, often supported by a dedicated workshop, which commonly forms an integral part of the roadmapping process (International Energy Agency 2014, Phaal et al., 2001, Phaal, 2004). Workshops provide a physical space for communication between participants from different parts of an organisation to produce, contribute to, or review the intended future path as well as for collective strategizing (Albright and Kappel, 2003). Once a roadmap is developed, different versions of it can be developed to show different information and to communicate with different audiences and stakeholders (Albright and Kappel, 2003, Kappel, 2001, Kerr and Phaal, 2015). For example, derivative roadmaps can be created for potential investors, strategic planners, senior management or technical teams, or those responsible for intellectual property and patents and those dealing with public outreach (i.e. marketing).

Roadmapping has previously been deployed to support space sector programmes (see (NASA 2014)) as well as the development of fusion (see section 4, step 2). However, these instances represent an application of the method to help guide overall industry direction – and can be classified as "sector-level roadmaps", see (Phaal et al., 2009) – rather than as roadmapping to actively support the management of innovation and the commercialisation process for a limited application. It has previously been applied to agile innovation, including to support agile management in manufacturing firms (Carlos et al., 2018) and to enable agile software development (Ozaki et al., 2015). Similarly, a roadmapping framework has been developed specifically to support agile start-ups, which has been applied extensively, see (Leffingwell, 2018). However, the focus has been on its utility to support agile management in established organisations pursuing incremental innovation rather than for actively supporting agile innovation in disruptive grand-scale missions such as in fusion or the space sector. Roadmapping potentially provides a useful method to support such missions and exists as a critical gap in its applications.

Fusion start-ups are pursuing programmes that entail highly complex hardware development with an ambitious vision and are subject to significant uncertainty and risk. Such uncertainty and risk can be managed through appropriate organisational design and practices (McCurdy, 2001). Roadmapping, as a tested research method, as well as a functional management tool, can be deployed to support the determination and execution of the best path forward. The combination of these factors makes action research, in this case, via a case study, the most suitable approach to deploy the method. The following sections detail the specific roadmapping process and resulting roadmap developed for Tokamak Energy Ltd as a fusion start-up case study. The process is designed to support the approach outlined in section 2, and specifically to facilitate high-level programme planning, the management of the innovation process, and to enhance communication of the future strategy.

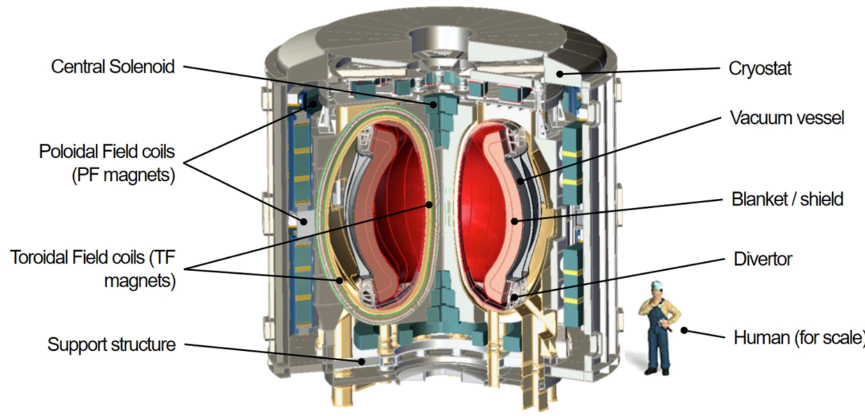

Figure 6. Concept diagram of Tokamak Energy's spherical tokamak using HTS magnets.

4. Tokamak Energy's Goal and the Production of a First-pass Technology Roadmap

4.1. Tokamak Energy's vision and mission

Tokamak Energy's goal is to demonstrate the commercial viability of fusion energy in the near-term using a compact spherical tokamak in which the magnets are made using HTS (Sykes et al., 2018, Costley, 2019, Windridge, 2019). A schematic of a spherical tokamak concept, similar to that envisaged by Tokamak Energy, is shown in Fig. 6. A spherical tokamak is a particular configuration of three of the principal tokamak parameters – size, magnetic field and shape – and appears to be particularly suitable for compact devices. In shape, it represents a "*cored apple*" rather than a "*ring doughnut*" which is the shape of a conventional tokamak. The spherical tokamak has been found to have benefits in terms of plasma performance, although it does have unique engineering challenges (Sykes et al., 2018). If these can be solved, the improved performance combined with HTS magnets is expected to open up a pathway to compact fusion devices of high performance (Costley, 2019).

In brief, Tokamak Energy's programme consists of building and operating a series of spherical tokamaks of increasing performance towards the stated goal and, where necessary, carrying out parallel R&D on key tokamak components, particularly HTS magnets, the inner radiation shield for the central solenoid and the divertor, which are key components, as labelled in Fig. 6. Many of the technical challenges for the fusion devices are similar to those being addressed in public fusion programmes and solutions being developed in those programmes can be used if the development is sufficiently advanced for the Tokamak Energy schedule. Spin-off opportunities that arise from the company R&D are identified and developed if commercially viable. Furthermore, all commercial aspects are kept under review and can influence the overall direction of Tokamak Energy's programme. The company has a highly skilled team of in-house scientists and engineers, as well as external contractors and consultants. It has collaborations with fusion laboratories and universities worldwide. The experimental work is undertaken in an innovative fusion laboratory set up in Oxfordshire, UK.

Tokamak Energy's primary goal requires demonstration of net energy production whilst accounting for the energy consumed in the balance of plant (engineering fusion gain $Q_{eng} > 1$) and having all the basic core components sufficiently developed to demonstrate scalability to a commercial fusion reactor. While precise engineering specifications of such a tokamak cannot currently be determined due to technical and commercial uncertainties, target high-level performance specifications can be identified. The tokamak must produce net energy controllably; it must be compact, easy to build, and be safe and reliable in operation; and it must demonstrate scalability to a commercial product (i.e. a FOAK commercial fusion reactor). The goal is well defined, but the steps required to achieve it are less so. The phases of innovation detailed in the S-T-A-M model (section 2) are useful as a means to provide structure for understanding the current position and required steps to commercialisation, i.e. to determine "how we get there". By setting Tokamak Energy's mission in the context of the S-T-A-M model, we can define the transitions that must be overcome on the path to achieving the company's goal. The current operating tokamak, ST-40, is advancing the understanding of several fundamental plasma physics and technical aspects, effectively reducing the risk of some technical elements that are important for the design and construction of a FOAK reactor. The next planned device, ST-F1, is aiming to demonstrate net power gain in the fusion plasma ($Q_{fus} > 1$) and will, therefore, overcome the S-T transition, realising Tokamak Energy's Wright brothers' moment". As such, ST-F1 represents the *breakthrough MVD* for Tokamak Energy. The device to overcome the T-A transition (the MVP) is ST-E1, for which the technology development will mostly follow, but in some cases overlap, with ST-F1. ST-E1 is thus intended to demonstrate the commercial viability of fusion energy. Naturally, challenges will remain beyond ST-E1; for example, issues such as financing (for construction), international licensing, scaling up supply chains and in the development of higher-performance materials to allow longer component lifetimes must all be considered in addition to reactor technology development. Steps to deal with these aspects are under development at Tokamak Energy.

4.2. Production of a first-pass roadmap

Technology roadmaps are typically developed through a multi-stage process. For the application to Tokamak Energy, we found it helpful to develop this via two principal stages: First, develop the basic structure, scope and organisation of the roadmap. After that, the technical aspects, internal links and content are developed to yield a "first-pass" roadmap. The first-pass Roadmap was produced through four steps, as shown in Fig. 7).

Step 1: Define the scope and objectives of the roadmap
The roadmap is intended to give an overview of the entire development programme towards the defined goal. However, it is also developed as a tool to assist with the management of technology development programme according to the agile innovation model. The roadmap must be consistent with the company strategic business plan. Hence the setting of goals and objectives for the roadmapping activity was carried out in close consultation with senior management.
Step 2: Select reference roadmapping processes
Technology roadmapping is a well-developed technique, and different roadmapping processes have been developed. Several roadmapping processes were particularly useful as a reference point for

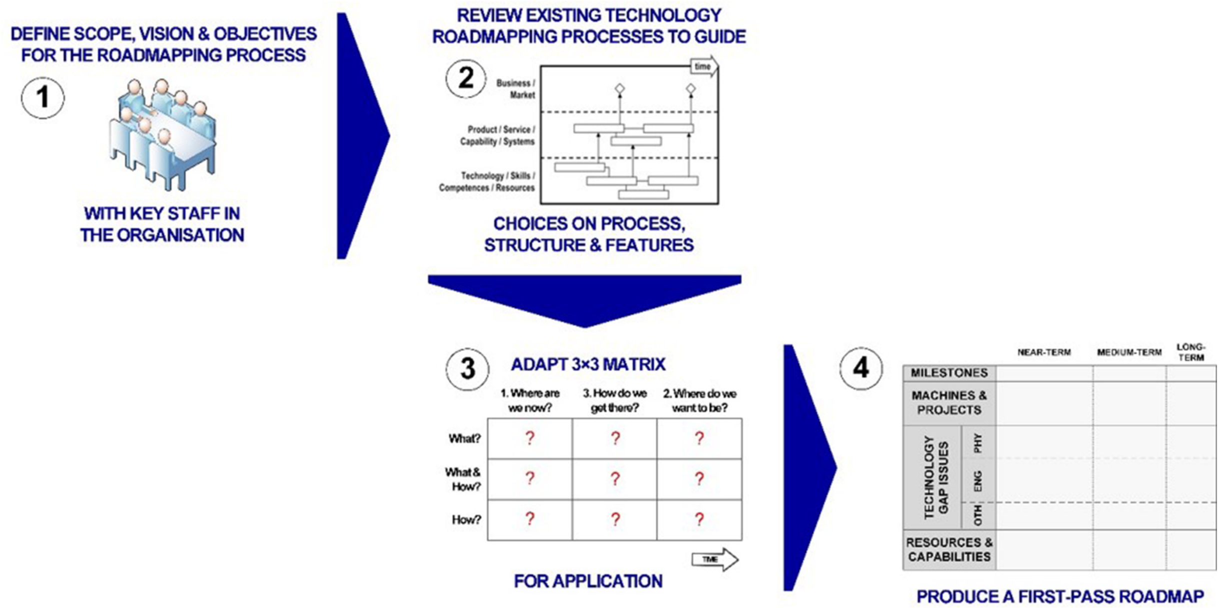

Figure 7. The process to develop a first-pass roadmap for Tokamak Energy (steps 1 to 4)

the approach developed here. Specifically, we used The Institute for Manufacturing (University of Cambridge) T-Plan (Phaal et al., 2001), EIRMA's (European Industrial Research Management Association) roadmapping process (European Industrial Research Management Association (EIRMA) 1997), Sandia National Laboratories roadmapping for strategic business development (Garcia and Bray, 1997), the International Energy Agency roadmapping process (International Energy Agency 2014), and the guide to roadmapping for the U.S. DoE Environmental Management (United States Department of Energy 2000). For the development of the roadmap structure, we used Motorola's car radio roadmap (Willyard and McClees, 1987), Lucent Technologies corporation roadmaps (Albright and Kappel, 2003), and the Office for Naval Research guide to modelling roadmaps (Zurcher and Kostoff, 1997). For the organisation of the workshops, we used the T-Plan framework (Phaal et al., 2001), the International Energy Agency roadmapping process (International Energy Agency 2014) and the LEGO Group roadmapping for management (Kerr et al., 2017).

There have been several roadmaps developed in support of the public fusion programme (see (Phaal, 2011)), but none of these are particularly useful for application to fusion start-ups. Probably the most developed is the European fusion roadmap which outlines the expected route to commercialisation, mostly using tokamaks, for the public fusion programme in Europe. Two iterations of the roadmap have been published, five years apart, with the most recent in 2018 (Eurofusion 2018). While the roadmap provides insights on the required direction of travel, detailing high-level objectives, scientific milestones and broad technology development needs – specifically those related to ITER and its satellite R&D programmes towards DEMO – it does not define the "why" or "how". It is not clear how the roadmap aggregates all the technologies that need to be developed, and it does not describe how commercial drivers are used to drive technology development. Therefore, the European fusion roadmap represents a technology-push system and also reflects the underlying linear model of innovation upon which the public programme operates, as outlined previously in section 2.1. It is not useful as a foundation to support the development of a roadmap for fusion start-ups.

Step 3: Determine the basic structure of the roadmap

The current position of the development programme and the defined vision or goal(s) essentially define the boundaries of the roadmap. The boundaries are most instructively outlined using the S-T-A-M model, and, in particular, the transitions define the significant steps in the programme: the $Q_{fus} > 1$ (the breakthrough MVD) and the $Q_{eng} > 1$ (the MVP) milestones. The approximate timescale is thus displayed at the top of the roadmap and the devices; ST40, ST-F1 and ST-E1, and the parallel R&D on critical technologies such as the HTS magnets, are major elements of the development programme and are displayed on the upper layers. To put depth into these elements the questions "where are we now?", "where do we want to be?" and "how can we get there?" must be addressed. It is convenient to use a 3 × 3 matrix to determine a skeleton before loading the roadmap (see Fig. 8). For the first-pass roadmap, only placeholders are needed. The essential point is to ensure that all scope is included.

Step 4: Develop the layers of the Technology Roadmap

Typically, the layers of a roadmap represent market, product and technology (see Fig. 5 in section 3). The "Machines & Projects" layer, as detailed in Step 3, shows what is required to build and test the technology to be developed and thus essentially answers the

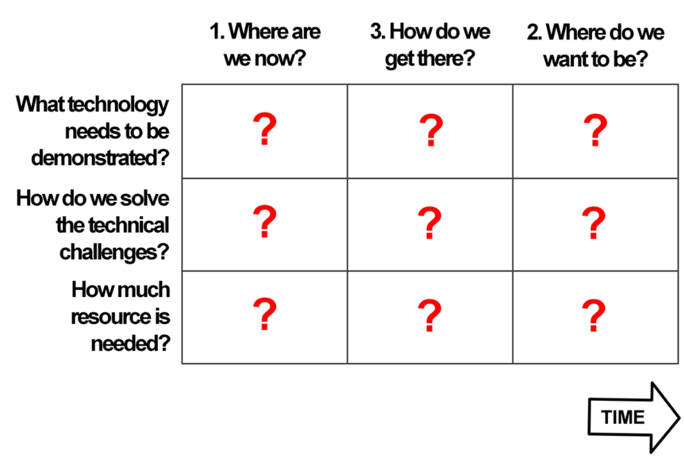

Figure 8. The 3 × 3 matrix used to determine the basic structure of the roadmap per step 3 of the process. Questions on the y-axis can be adapted dependent on the scope of the roadmap being developed. Adapted from (Phaal et al., 2010) with permission of the author and the University of Cambridge.

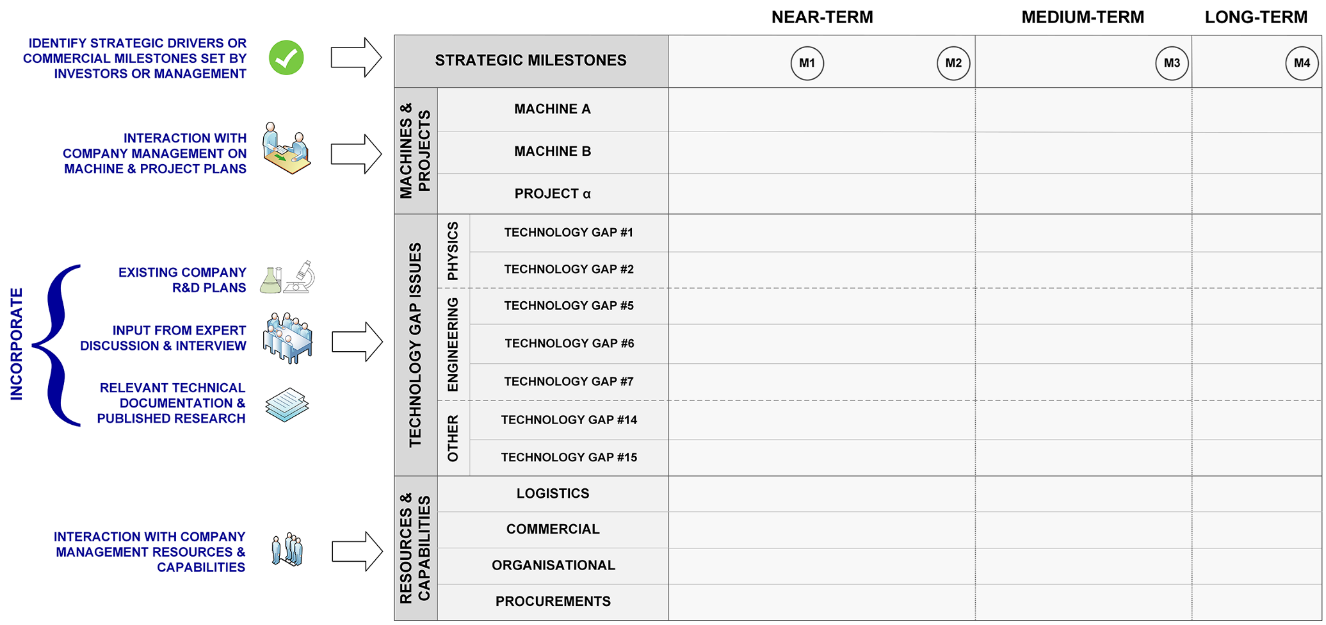

Figure 9. Close-up of step 4 in the production of the first-pass roadmap for Tokamak Energy and the basic structure and outline content of the roadmap

questions related to "what". However, given the scale of the technology development for Tokamak Energy, the "how" is separated into two distinct layers. "Technology Gap Issues" identifies areas in the state of technology development where there is considerable uncertainty, and further development is needed (as technologies are at low Technology Readiness Levels, see 5.1.5). "Resources & Capabilities" details the auxiliary support or logistics that are needed to close the gaps. The lower layers go on to deal with the enabling facilities, resources and logistics. A layer detailing "Strategic Milestones" represents the exploitation and development of commercial activities; in roadmapping terms, it represents the "why". Strategic milestones are set by investors and business leaders, and thus although the structure of the roadmap is predominantly focused on R &D, it is tethered to commercial drivers. Thereby the basic structure and outline content of the roadmap is determined, as seen in Fig. 9.

5. The Tokamak Energy Roadmap: Content Development and Review

Considerably more depth in the roadmap is required in order for it to fulfil its intended purpose. In the first instance, we developed content in consultation with key staff within Tokamak Energy. Subsequently, the content was reviewed and further developed in two dedicated review workshops involving key staff at Tokamak Energy. Further consultations with experts, as well as analysis, were undertaken on specific TGIs via focus workshops and the use of analysis tools, respectively. The steps involved are summarized in Fig. 10.

5.1. Content development

At the upper levels, the company's strategic milestones, the main stages in the existing and planned fusion devices, and planned steps in the parallel in-house R&D programmes are shown (see Fig. 9). Of course, detailed plans exist for these machines and projects, usually in the form of Gantt charts. The high-level information in the roadmap represents key steps in these plans. The initial loading of the roadmap for these levels mainly involved importing existing information.

5.1.1. Technology Gap issues

The specific challenges in technical understanding or technology development that must be overcome for Tokamak Energy to realise commercial fusion can be broken down into specific Technology Gap Issues (TGIs). These are areas of physics or technology where there is presently considerable uncertainty or lack of knowledge, and where that leads to uncertainty in the design and performance of the planned first-of-a-kind fusion reactor. In other words, the Technology Readiness Level (TRL) of some of the technologies needed for ST-E1 are currently low (see 5.1.5). More information and knowledge, and possibly dedicated R&D, is needed to reduce the uncertainties.

Dividing the overall development challenge into separate TGIs is consistent with an agile approach to innovation. Even though ST-E1 will ultimately integrate all technical aspects, certain problems can initially be solved independently, and some decisions can be deferred until later in order to make faster progress in the near-term. The strategy to develop technology in parallel is analogous to NASA's Mercury & Gemini programmes in which technology and technical know-how were progressed concurrently via separate development streams to support the Apollo mission to land a man on the moon.

For Tokamak Energy, 15 TGIs were initially identified, and most fall into three distinct categories: *physics, engineering*, and *other* technology issues that relate to the execution of the programme. The issues are summarised in Table 2. Although each TGI was defined independently and specifically for Tokamak Energy, unsurprisingly there are significant overlaps with previously defined technical gaps from other tokamak fusion programmes, for example, those detailed in (Donné et al., 2017) and (Zarnstoff and Goldston, 2017). Several of the TGIs are of relevance to non-tokamak fusion approaches, too.

By definition, the resolution of all TGIs is essential to achieving mission success. However, TGIs vary in nature and difficulty of resolution. For example, TGI #1 (Energy confinement time) requires a certain level of technical and plasma performance to be achieved and a corresponding understanding of the physics to be confident that the required net power gain can be achieved. In contrast, TGI #9 (Fusion materials) requires the characterisation of the performance of existing materials in as yet unexplored ranges and possibly the development of new materials. Several TGIs will have a relatively high impact on the feasibility and design of the intended future fusion device (ST-E1). For example, if in order to achieve the required energy confinement time a toroidal field of 6 T (Tesla) is needed, this will have a significant impact on the design of the tokamak. In comparison, a field of only 3 T may be easier to engineer and may thus result in the realisation of a smaller reactor. These TGIs are described as "high-leverage" , and currently,

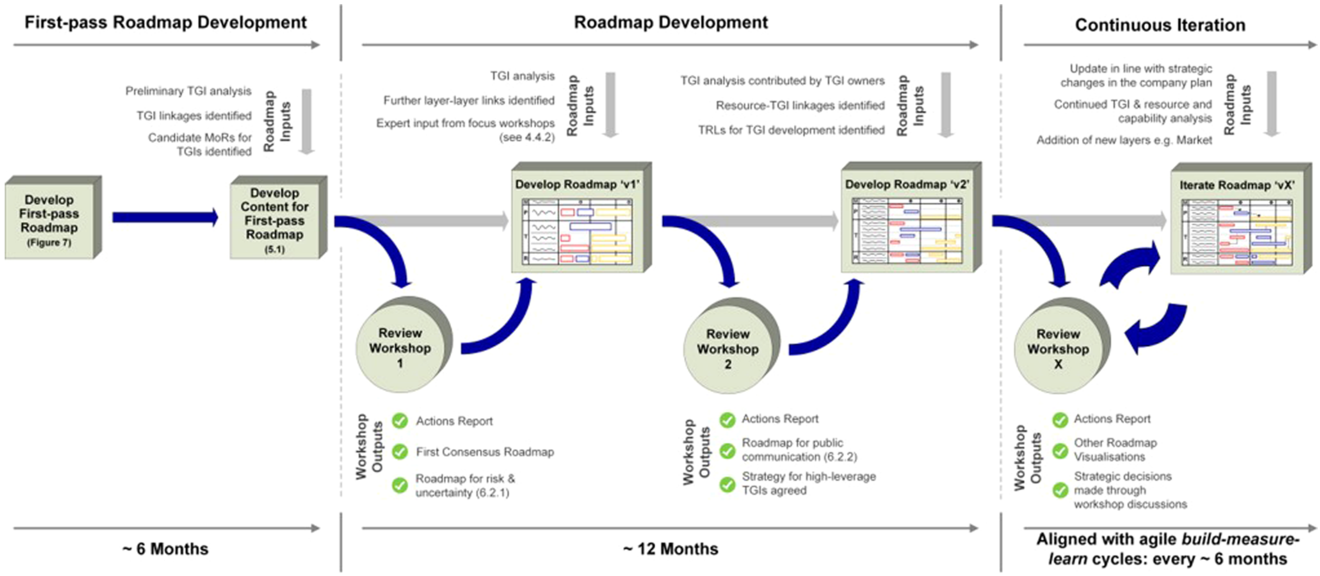

Figure 10. The roadmap development process, derived from application to Tokamak Energy (the inputs and outputs can be altered depending on the application and needs)

four have been identified for Tokamak Energy: #1 (Energy confinement time), #5 (HTS magnets), #6 (Divertor) and #7 (Radiation shield for central column).

In some cases, the technical challenges can be further broken down, and sub-TGIs created; similar to the sub-layers described in (Phaal, 2004). Some of the TGIs where it is not essential to resolve them in the near term, for example, TGI #12 (Tritium breeding and self-sufficiency) are likely to become high-leverage and to be divided into sub-TGIs in the future. However, all TGIs that can be identified at this stage are included in the roadmap to ensure that some level of development activity is underway at present. As the development progresses, other TGIs may arise. However, in general, it is expected that the number will diminish with time as individual TGIS are resolved.

5.1.2. TGI Analysis

Since the TGIs are main elements of the development programme, they were subject to a more in-depth investigation. A careful assessment of the current level of development was carried out; typically, this involved a review of the status of public tokamak programmes and its relevance to the Tokamak Energy programme. The activity was primarily an analysis and review exercise. In some cases, it is clear that dedicated R&D is required because results are not likely to be available on the needed timescale. In these cases, dedicated internal development programmes have been formed. Relevant external documents, particularly in the form of journal articles and reports from national laboratories, as well as input from subject matter expert consultants, were also gathered and analysed. The documents created through this process were used as templates to capture content to be translated into the roadmap and to form a library of supporting material.

5.1.3. TGI interdependencies (linkage grids)

Many of the technical aspects of TGIs are inextricably linked, and these linkages must be captured. For example, the divertor (TGI #6), the radiation shield for the central column (TGI #7), and access for diagnostics and heating beams (TGI #4) all require space and thus can affect the ability to breed tritium (TGI #12) as well as the ability to carry out remote handling (TGI #10). Although tritium breeding is not required for ST-F1, it will be essential for ST-E1, and so early-stage solutions for ST-F1 that can be extrapolated to ST-E1 are favoured. Linkage grids are an effective tool for capturing these links and are commonly adopted in roadmapping to identify interdependencies and integrate roadmap layers (Phaal et al., 2001, Phaal et al., 2005). For the first-pass roadmap developed for Tokamak Energy, linkage grids facilitated the understanding of high-level dependencies across TGIs, to ensure that disparate and parallel technology development streams will be developed with integration in mind, as shown in Fig. 11. The linkages – shown as red dots – are quantified in detail for the Tokamak Energy programme.

5.1.4. TGIs: Methods of Resolution

To progress towards a point where ST-E1 can be designed and built with confidence, a solution path needs to be identified, and a strategy developed to resolve each TGI. Various methods of resolution are possible. For example, for physics TGIs, much relevant information can be learnt from the operational programmes of existing and future spherical tokamak experiments such as MAST-U at Culham Centre for Fusion Energy, UK, and NSTX-U at Princeton Plasma Physics Laboratory, US. It may just be a matter of importing the techniques developed in those programmes. Similarly, some of the required technology is under development in the numerous existing external R&D programmes, laboratories supporting public fusion programmes, or even from other industries. For other TGIs, for example, the development of HTS magnets, dedicated in-house R&D is needed due to comparatively little relevant external development. In this area, there is also the possibility to develop Intellectual Property (IP), which is, of course, of significant importance for all private organisations developing technology. For some TGIs, work with collaborators or commissioned work by external contractors may resolve the issue. For less urgent, typically longer-term TGIs, a "watching brief" may be sufficient; whereby relevant external R&D is tracked, including for developments in sectors beyond fusion. For each TGI, a preferred method of resolution was identified and displayed in the roadmap.

The involvement of external collaborators, which are heavily involved in some TGIs, helps foster the creation and nurturing of an *innovation orchard* for fusion start-ups. An innovation orchard is a concept whereby companies seek collaboration with universities, industry, and government laboratories to leverage expertise, equipment or ideas to support inbound innovation on technology development (Singer and Bonvillian, 2017). From the perspective of fusion start-ups, inbound innovation from collaborators in their innovation orchard can yield significant value at relatively low cost. From the perspective of potential collaborators, start-ups should be viewed as "industry" driving the

Table 2
Definitions of the Technology Gap Issues identified for Tokamak Energy.

Type	Technology Gap Issue (TGI)	Description
Physics	#1 Energy confinement time	The scaling of the energy confinement time with device parameters, particularly size, field and shape, is a high impact element in the design of tokamak fusion reactors, see (Costley, 2019). The scaling for conventional aspect ratio tokamaks is well developed, but the scaling for spherical tokamaks requires further development and validation, see (Buxton et al., 2019).
	#2 High gain and burning plasma physics	A high-gain plasma (Q_{fus} > 3) will incur self-heating (where the fusion plasma heats itself due to alpha radiation). Potentially as yet experimentally unseen plasma physics phenomena could occur and significantly affect plasma behaviour and performance (positively or negatively).
	#3 Plasma control	Long-pulse, steady-state plasmas are essential for a viable fusion reactor. Plasma ramp-up, ramp-down and control (for instabilities and disruption mitigation or avoidance) must be understood, designed for and, in the case of disruption mitigation, demonstrated. See (Gryaznevich and Sykes, 2017).
	#4 Auxiliary plasma systems (heating, current drive, fuelling, & diagnostics)	Customised technology is required for heating, current drive (non-bootstrap fraction), fuel injection, and for making key in-vessel and plasma measurements (diagnostics) for burning plasma operation.
Engineering	#5 High-Temperature Superconducting (HTS) magnets	Development of HTS for practical use in fusion is limited. Technology must be developed in key areas: electromechanical design (stresses, joints, cables and connections), design for quench protection, design of cooling systems, design for use under neutron irradiation (including to understand the level of shielding required, which impacts device size). Additionally, the global supply of HTS tape is limited, and the performance of existing supply varies. Also, see (Bruzzone, 2010).
	#6 Exhaust power handling (Divertor)	Tokamaks must have sufficient power handling capability to handle the power exhausted from the plasma (via the divertor). Although various divertor designs have been developed in public fusion programmes, a design suitable for a spherical tokamak must be developed, see (Costley, 2019).
	#7 Inner radiation shield for the central column	The geometry of a spherical tokamak necessitates a relatively thin central column. A dedicated radiation (neutron) shield must be designed to protect the HTS magnets in the central column, which in turn impacts minimum device size. A functional design, materials capable of handling high heat loads and neutron loads, as well as an effective cooling mechanism, must be developed. See (Costley, 2019, Windsor et al., 2015, Windsor et al., 2017, Windsor and Morgan, 2017).
	#8 Plasma-material interactions	Plasma-facing and in-vessel components (e.g. the first wall) could be damaged due to energetic particle bombardment, in particular by a high fusion neutron flux which will limit component lifetime. Materials must be developed to achieve the desired performance.
	#9 Fusion materials	The development of fusion materials is essential for many components and systems. Structures inside a fusion reactor will be subject to high fusion neutron flux and high heat loads, as well as thermal ramping (causing fatigue) and large temperature gradients (inducing stress), which may limit operational lifetime. Suitable materials must be selected, developed through R&D and qualified for use in the fusion environment.
	#10 Remote handling and maintenance	Components (e.g. divertor, first wall, blanket) in a DT fusion reactor will become radioactive after reactor operation due to neutron irradiation. Repair and replacement must be carried out by remote handling. Dedicated technology must be developed for the spherical tokamak.
	#11 Tritium handling, recycling & supply	Specialised systems and procedures are required to handle and recycle tritium fuel. Challenges in handling tritium, such as retention in the first wall and the development of a water detritiation system, require solutions. The supply of tritium from an external source, alongside the associated safety, regulatory and licensing aspects must also be considered, see (Pearson et al., 2018).
	#12 Tritium breeding & self-sufficiency	Fusion reactors must breed tritium via a lithium-based breeding blanket. A blanket must be designed to produce more than one tritium atom for every neutron produced by the fusion reaction and to extract the produced tritium effectively. A dedicated blanket design for a spherical tokamak is required, as, in particular, a spherical tokamak does not permit breeding in the central column due to space restrictions, thus impacting minimum device size. Also, see (Menard et al., 2016, Pearson, 2020).
Other	#13 Energy generation	The blanket described in TGI #11 must transfer neutron energy to thermal energy, which can be converted into useful electrical energy or other process heat applications. The tritium breeding blanket and energy generation mechanism are thus inherently linked. For applications such as hydrogen production, new ex-vessel systems must also be developed.
	#14 Economics of fusion for energy	While relatively small spherical tokamak reactors may be technically feasible, for the commercialisation of fusion they must also be commercially viable. Assessments of the commercial feasibility of spherical tokamak power plant, possibly through a modular approach, is required to optimise performance parameters, especially as regards the power and size, see (Chuyanov and Gryaznevich, 2017). Although electricity generation is a key focus, the economic viability of other commercial pathways should be considered.
	#15 Licensing, regulation and safety	The location of a suitable site, the development of a suitable regulatory framework, and securing necessary construction, operation, and decommissioning licenses represents a lengthy, multi-stage process. Engaging with regulators at an early stage will ensure that fusion systems are designed appropriately to follow procedures, thereby ensuring the end product, i.e. the ST-E1 FOAK fusion reactor, can be built and operated.

requirements for new R&D or for utilising existing knowledge and expertise, rather than as competition.

5.1.5. Technology Readiness Levels

Technology Readiness Levels (TRLs) as developed by NASA to assess technology development for space technology are an established metric for assessing and displaying progress in the development of technology (Mankins, 1995). They assess demonstrable technology maturity or “readiness” on a scale of 1 to 9, whereby TRL 1 is given to a technology in which only basic principles are understood with degrees of progression towards TRL 9, which represents that full operation in the relevant environment has been demonstrated. TRLs combine well with the process of roadmapping as they provide a metric of “where we are now” on the path to “where we want to be”. For Tokamak Energy, TRLs are used to measure the progress of technology development in the roadmap and as a means to display the current state of development succinctly. Assigning a TRL for a given TGI is a subjective exercise; it requires expert analysis and review. Of course, for the resolution of a single TGI, it is not simply one individual component that must be developed, but the integration of several different components and systems. For this System Readiness Levels (SRLs) can be used to determine the maturity of combined technologies. The assignment of TRLs

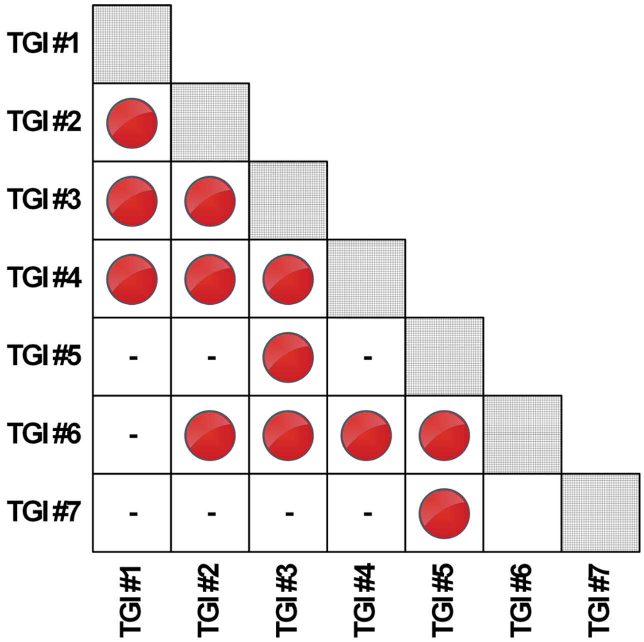

Figure 11. Technology Gap Issue Linkage Grid

and SRLs and their integration with the roadmapping process is an ongoing exercise for Tokamak Energy.

5.1.6. Commercial aspects

As explained in Section 2, a key feature of agile innovation is that commercial aspects are always under development and review, and the technical development programme can be adjusted in response to commercial aspects – the “technology push” and “commercial pull” of agile innovation. Thus, work on commercial aspects is part of the Tokamak Energy programme and so is included in the roadmap. Mostly, there are two types of commercial activity: those that relate to the principal goal – the demonstration of the commercial viability of fusion energy – and those that relate to the commercial exploitation of spin-offs, which can arise from in-house R&D activity. For the former, ongoing studies of the economics of fusion energy are part of the development programme, see (Chuyanov and Gryaznevich, 2017). For the latter, opportunities are sought to exploit the IP that the company has secured through its in-house R&D programme, appropriately protected by patents. Spin-off technology success and associated revenue streams are a key part of the fusion start-up business model.

5.1.7. Resources & capabilities

Closely linked to the technical programme is the development of resources necessary to enable progress with the technical elements. Significant financial investment; a workforce of professionals, designers, technicians and administrators; various hardware; and, in some cases, novel materials for which considerations regarding supply chain and specialised manufacturing processes, amongst other things, are necessary. These aspects are displayed in the lower layer of the roadmap.

5.2. Developing the Roadmap through Workshops

The bulk of the roadmap development thus far described was carried out by a small dedicated roadmapping team , alongside consultations with appropriate experts. The involvement of experts and staff with different elements of the programme will naturally add content and accuracy to the roadmap and build consensus within the team. Workshops are typically deployed to capture such contributions, whereby a team works collectively to identify and develop the best path towards the specified goal(s) (Albright and Kappel, 2003, Amer and Daim, 2010, Phaal, 2004). Workshops were used to develop the roadmap for Tokamak Energy (see Fig. 10).

5.2.1. Tokamak Energy workshop overview, scope and schedule

Two half-day team workshops were run spaced apart by about six months, the first in May 2017 and the second in November 2017. The scope of the first workshop was to validate the structure and content of the first-pass roadmap. Key staff generated ideas as a collective effort, mainly developing the scope of future R&D projects and the high-level performance requirements of future machines, which is driven by an understanding of the TGIs that must be developed. The second workshop focused on identifying methods of resolution for the four high-leverage TGIs. Typical outputs of the workshops are shown in Fig. 10. Following workshops, action reports were produced outlining the main activities from the workshop with actions to progress the development. Action reports were disseminated internally within Tokamak Energy along with an updated roadmap with agreed content and structural changes.

5.2.2. Workshop participants

For effective roadmapping, workshops should involve participants from several functions of an organisation to reflect both the technically-oriented and commercially-oriented viewpoints. In high-tech start-ups, in particular, there is usually an abundance of technical knowledge. However, to enable effective innovation in such environments, there is a need to complement scientific minds with more commercial and entrepreneurial minds (Tura et al., 2017, Park, 2005). The workshops at Tokamak Energy involved between 8 and 10 participants guided by two facilitators (two of the authors of this paper; Pearson and Costley). The participants had a range of roles in the company – scientific, technical, commercial development, planning etc – but given the technical nature of the challenge, there was a concentration on scientific and technical aspects. Accordingly, the participants were divided into three categories: executives, technical managers and technical experts, as shown by the examples in Fig. 12.

Figure 12. Roles of roadmapping workshop participants at Tokamak Energy

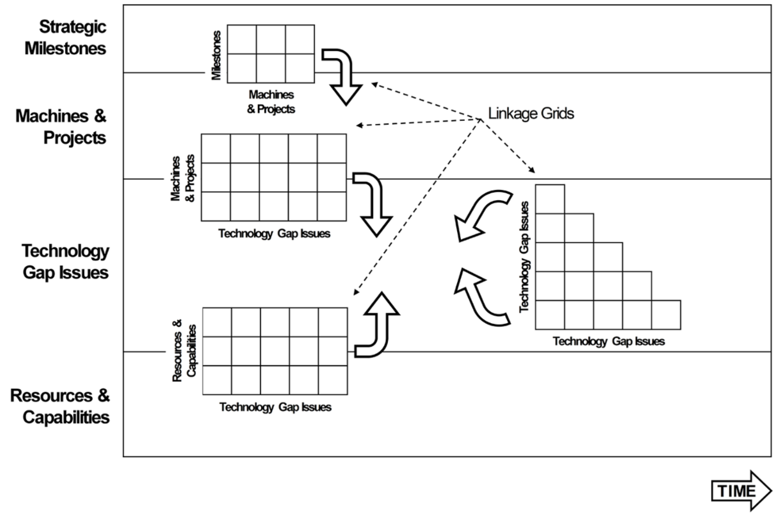

Figure 13. Linkage grids for the Tokamak Energy Technology Roadmap, to analyse crosslinks between layers. Based on Fig. 6 in (Phaal and Muller, 2009), adapted with permission.

5.2.3. Workshop activities

Both workshops followed the same broad structure, which can be distilled as six key steps, detailed below:

1 **Introduction:** Objectives and intended outcomes for the workshop are delivered by the facilitator, alongside opening remarks from an executive - typically, the CEO.
2 **Group activity:** Participants are divided into three groups to review the roadmap (for the first workshop, this is a review of the first-pass roadmap). Each group contains one participant from each of the functions outlined in Fig. 12 to enable cross-cutting discussion. The group reviews the roadmap per the workshop objectives, providing new ideas or new data by interacting with a printed copy of the roadmap. As an example, in workshop 2 for Tokamak Energy, participants reviewed high-leverage TGIs one-by-one, recording ideas on post-it notes.
3 **Plenary activity:** groups discuss their ideas with other groups, moderated by the facilitator(s). Ideas and data are collated and recorded towards a consensus.
4 **Iteration:** steps 2 and 3 are repeated as many times as appropriate until objectives have been achieved. Typically, this is performed by reviewing one layer of the roadmap at a time.
5 **Summary:** a final plenary is held to identify the most important outcomes of the workshop to inform the generation of the action report (see 5.2.1).
6 **Consolidation:** required changes to the roadmap, alongside key outcomes and actions, are reviewed by the roadmapping facilitator (s), and agreed with senior managers or executives, and draft changes are issued.

5.2.4. Focus workshops

Many roadmapping processes depend on workshops for idea generation. Start-ups are constrained in terms of personnel, time, and resource. Accordingly, the process was adapted for the Tokamak Energy application such that workshops were a space for collective review and consensus on strategy. In parallel, separate “focus workshops” were deployed to provide an alternative means to generate technical content, which involved semi-structured interviews with subject matter experts (per (Harrell and Bradley, 2009)). Focus workshops can, therefore, be considered as a tool akin to those outlined in sections 5.1.2 to 5.1.5. For Tokamak Energy, focus workshops were used to develop content for TGIs by leveraging ideas and knowledge from consultants.

After the two workshops, and with input from several focus workshops, the Tokamak Energy roadmap and process was developed and embedded within the company. In mid-2018, the roadmapping process -developed as presented in this paper - was transitioned to a senior manager within the company. The process was developed sufficiently to be used as a tool for practical management. However, suggested steps for the future development of the process were also provided, which are described in section 7. During the deployment of the roadmapping process, the roadmap started to inform management and be used for strategy development, which is detailed in section 6.

5.3. Developing the Technology Roadmap outside of workshops

Many roadmapping processes make heavy use of workshops. The core content of the roadmap for Tokamak Energy was developed through focus workshops as well as through TGI analysis, the development of additional linkage grids and incorporation of TRLs, as outlined in section 5.1. However, much of the roadmap content was developed between workshops, and workshops were instead used as a dedicated space for review, adjustment, and building consensus.

A particularly important activity was the further development of the TGIs and particularly those related to longer-term challenges. Uncertainties associated with longer-term TGIs can have an impact on current and planned near-term technology development or designs. Ideas or data from internal and external experts provided greater depth to the TGI analysis, particularly via focus workshops as a means to elicit that information, and thus the roadmap was appropriately updated.

The use of linkage grids was expanded to show relationships between layers beyond just technical links: for example, investor-set milestones, machines and projects, and resources and capabilities were all linked via additional grids, as shown in Fig. 13. Because of programmatic priorities, different layers of the roadmap effectively “push” and “pull” one another. The commercial “pull” of strategic milestones, derived from the business plan, sets targets for machines and projects and thus informs technology development. In the opposite direction, the limits of technological capability or the rate of development can “push” the timescales for machines, which can consequently impact higher-level milestones. Linkages between TGIs and machines are especially important. They enable the specification of the machines and their experimental programmes, and the results obtained in the operating phases, to address the key technical uncertainties. Similarly, linkage grids can be used to evaluate the resources and capabilities required to develop future TGIs. For example, for a currently non-essential TGI; remote handling technology (TGI #10), it provides initial

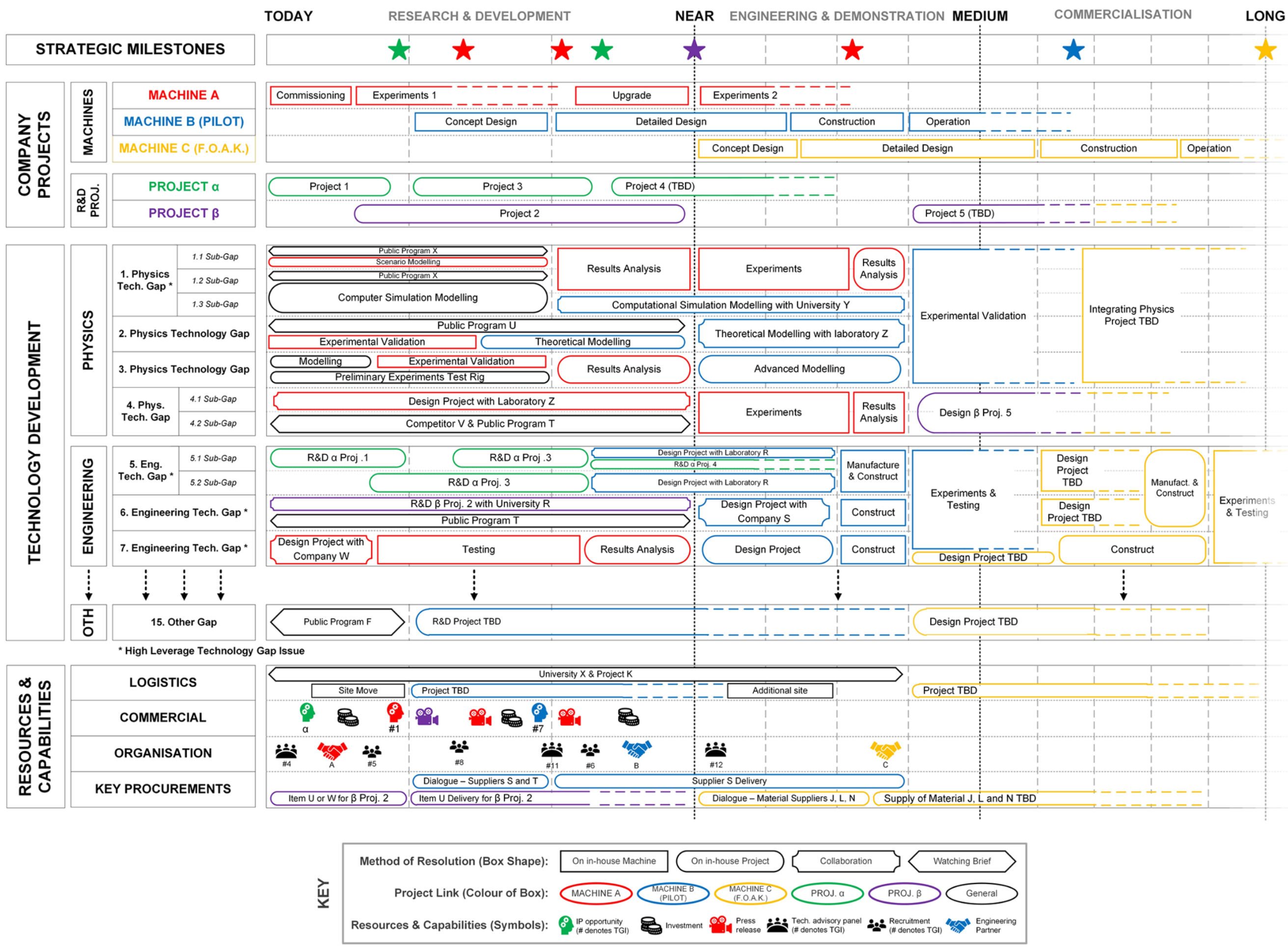

Figure 14. Features and content based on the Technology Roadmap as developed for Tokamak Energy. Precise details are not shown respecting Tokamak Energy confidentiality requirements.

estimates of the cost, materials required, site license conditions, and IP opportunities; thereby effectively resource-loading - or even "opportunity-loading" (showing where innovation could take place) - the high-level TGI development path shown on the roadmap . The linkage grids developed, therefore, add depth to the content of the roadmap, improve consistency between the layers and enhance the overall efficiency and robustness of the intended programme.

5.4. *The Tokamak Energy Technology Roadmap*

The results of the roadmapping process are captured in the full technology roadmap shown in Fig. 14. The time horizon shows the short-, medium- and long-term activities with an expanded time scale in the near term where naturally there is more detail in the programme elements. Some TGIs have sub-TGIs providing a higher level of detail, especially on issues that require a higher level of focus. Other TGIs are less developed (as before, typically, those relevant to the longer-term). The roadmap incorporates colours and shapes as a key design feature following the method in (Albright and Kappel, 2003). Colours illustrate a link between activities shown in TGIs to a specific project or machine. Similarly, the shape of the box around an element illustrates the expected method of resolution for any particular TGI activity, which allows the roadmap to show collaborators or work ongoing elsewhere. The symbols shown in the resources and capabilities layer provide a visual aid for the ease of viewing of the high-level resource requirements that are needed to support the overall programme. Detailed technical content exists at the lower levels of the roadmap, which cannot be seen in static and printed version in Fig. 14.

5.5. *Technology Roadmapping as an ongoing process*

Naturally, a multi-faceted R&D programme is dynamic, and there will be developments in both the in-house activities and relevant external fields that will influence the details of the programme. In order to retain value as a functional tool, roadmaps must be updated periodically to capture developments and to reflect progress in the development lines, or to account for strategic changes. All accompanying tools – linkage grids, TRL assessments, and TGI analyses – must be frequently updated. The timescale for updating will depend on the specific development activity. As a guiding principle, the most effective mode is to update the roadmap to match agile build-measure-learn hardware development cycles. Such updates could be done for the roadmap as a whole, or for individual TGIs that may advance in parallel but at different rates. As shown in Fig. 10, it is anticipated that workshops will be used for this function. For the Tokamak Energy programme, this is expected to be approximately every six months.

6. Outcomes and uses of Technology Roadmapping

As mentioned in Section 5, there are multiple outcomes and uses of Technology Roadmapping. At Tokamak Energy, the process and the developed roadmap impacted planning activities, which supported the management of the innovation process and facilitated communication.

6.1. Roadmapping to support planning and guide innovation

The roadmap aids management in making effective high-level decisions. The colours and shapes on the roadmap, as shown in Fig. 14, supports the identification of methods of resolution for specific technology challenges akin to a "make or buy" decision (see (Albright and Kappel, 2003)). In addition, for Tokamak Energy, this facilitates the identification of potential IP opportunities – and the timescale upon which such opportunities should be exploited – by determining which technology should be developed in-house and which should be developed through collaboration or outsourcing. Similarly, linkage grids allow the construction of coherent plans that align the functions of the company to ensure that all drivers, both technical and commercial, are considered in plotting the future pathway(s).

More generally, however, the layered and time-based structure of the roadmap provides a means to map the innovation system for Tokamak Energy. Many agile management techniques depend on visual methods. The developed roadmap is aligned with the phases of the S-T-A-M model with specific MVDs and an MVP outlined for Tokamak Energy, which means the innovation stages and the trajectory for commercialisation can be plotted and continuously reviewed. Viewing the innovation system in the format of a roadmap allows for potential challenges and opportunities to be plotted in line with the relevant part of the system that they might impact. The separation of the elements of the system in the roadmap also facilitates the agile and lean innovation approach todevelop technologies in parallel.

Experts and managers within Tokamak Energy have specialist knowledge, which, together with TGI analysis, facilitates the identification of the required technology development steps and the development of strategies to address or resolve the TGIs. Such indiviudals were identified and allocated as "TGI owners" to manage and develop information and strategies for specific TGIs. TGI owners are afforded the autonomy to decide how to solve the problem – perhaps with further input from other team members or expert consultants, via focus workshops (see 5.2.4). At a higher level, the roadmap, along with-corresponding linkage grids, facilitates understanding of how TGIs impact one another and allows the team to understand the importance of their development area on the overall Tokamak Energy programme. This provides two key benefits. Firstly, TGI owners can provide ideas on the way forward for specific TGIs, which can then be used to inform the development of a strategy for the overall programme. Secondly, as each TGI owner contributes their ideas and strategies, the roadmap provides a tool to guide the development of more detailed project plans, particularly where the integration of separate technology development streams is necessary.

For Tokamak Energy, the roadmap thus acts as a tool to guide technology planning while not disrupting current experiments or technology development activities, making it a useful agile management tool. Going forward, if the process and the roadmap are continually updated to be aligned with build-test-learn cycles, it will form a useful metric to measure agile innovation as a step-wise process. In effect, it can be used to capture and manage any changes in company strategy, as well as results or breakthroughs from technology development and experiments in the last cycle, informing planning for the next development cycle.

6.2. Additional uses of the Technology Roadmap

In addition to its primary role as a management tool to support programme development and facilitate agile innovation, roadmaps can have other useful functions. For example, they can be used in the management of uncertainty and risk (see (Ilevbare et al., 2014)) and in the communication of the planned development programme to different audiences (see (Kerr and Phaal, 2015)). Both such applications were considered for the Tokamak Energy roadmap.

6.2.1. Managing uncertainty and risk: Scenario Planning

Uncertainty and risk are unavoidable in cutting-edge, high-technology, development programmes (Phaal et al., 2010, Ilevbare et al., 2014). For fusion start-ups, uncertainties arise in several areas: for example, plasma behaviour as higher performance operating regimes are achieved, uncertainty in materials properties as materials are operated in new environmental regions, and supply and performance of key materials required for device construction such as HTS magnet tape. Other uncertainties and constraints, for example, the available workforce (including recruitment) and securing investment are also important aspects. Roadmapping allows preparation for times of predictable change and affords insights on how to react during times of unpredictable change. A roadmap can also be used as a tool to support scenario planning to help to manage these uncertainties and support strategic decision-making. In scenario planning, candidate future paths are developed to assess the level of risk in different elements of the programme. A forward path can then be chosen based on acceptable risk. Acceptable risk is not necessarily the level of risk with which one is satisfied. Instead, it is an understanding that while risk is unavoidable, when multiple paths exist and one path must be taken, the risks of pursuing that path are understood and accepted versus the alternatives (Derby and Keeney, 1981).

To illustrate the process, we consider a fusion start-up with two possible paths forward to the intended goal: the demonstration of a fusion device producing net energy gain, illustrated in Fig. 15. On one path; path "A", an intermediate device is built and technologies tested, and uncertainties de-risked through this device, while the second path;

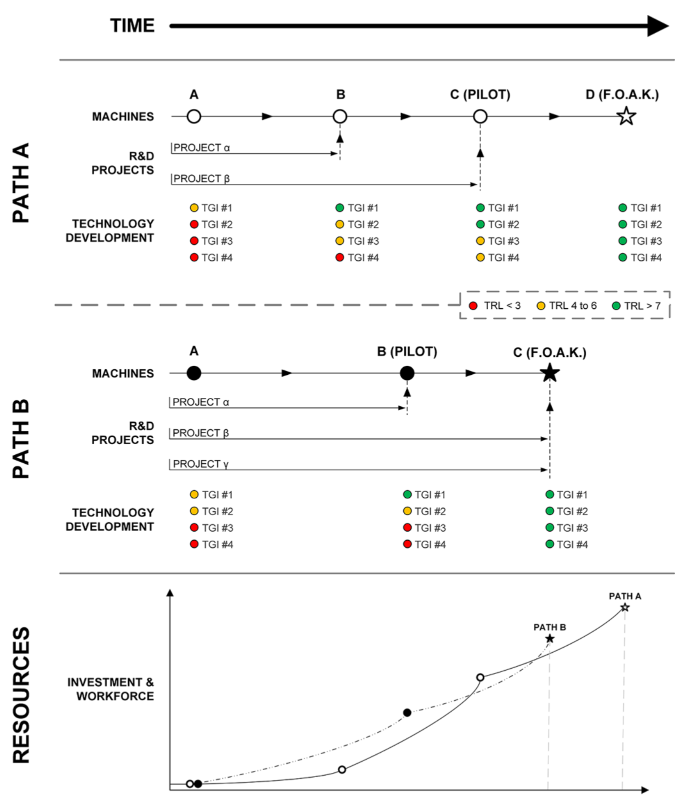

Figure 15. Comparison of two possible forward paths: path A and path B, in the development of a fusion device capable of net energy gain, produced using information from the technical roadmap. The key technical uncertainties, an assessment of the cost and time of the pathways can be compared relative to one another. Path A, where TGIs are de-risked to a higher level before making the next step, takes longer and has a higher total cost primarily because of the longer time to the FOAK device. Path B is likely to be cheaper and faster but carries greater risk and requires more resource in the near-term. Note: resources scale is arbitrary and for illustration only.

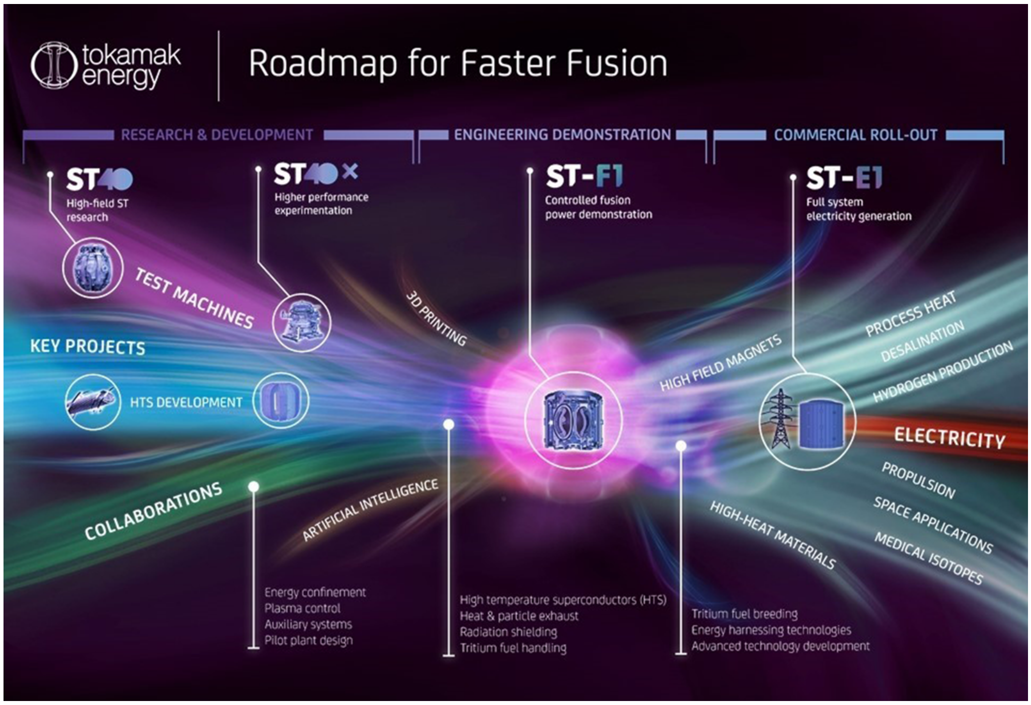

Figure 16. Structure and features of Tokamak Energy's "Roadmap for Faster Fusion", developed to support public communication. For a view of the current plan and timescales, see (Tokamak Energy Tokamak Energy Ltd Website).

path B, goes directly from current devices but has additional R&D on key components in which the results of the R&D are integrated later. Path "A" enables the testing of key components and materials in a relevant environment. It thus builds experience and knowledge, but inevitably takes longer, thereby potentially resulting in the integrated cost and time to the realisation of the goal to be higher. Path "B" could be faster and lower cost but, in comparison, carries higher technological risk. Such a process was used at Tokamak Energy. The information from the roadmap was transposed into a graphic showing device progression, dates of demonstrations, technologies to be developed (TGIs), and a plot estimating key resource requirements (workforce and cost). A traffic light system, using green, amber and red, was used to provide a simplified version of TRLs as a metric to show TGI progression, and thus the de-risking of technology over time. The path forward was chosen based on an assessment of the risks and uncertainties associated with each which allowed the company to move forward with plans based on accepted risks.

6.2.2. Supporting public communication

Roadmaps with the level of depth and type of details, as shown in Fig. 14, are useful for staff within a company or organisation for the optimisation and management of the path forward. The roadmap at Tokamak Energy was used as a visual platform for communication both in workshops and for general dialogue between staff within the company. However, other audiences are also interested in the intended path forward to, for example, potential investors, scientific journalists and researchers in related fields. Different views of the roadmap can be created for these audiences.

At Tokamak Energy, a roadmap for public communication has been created, which is shown in Fig. 16. The public communications roadmap shows the requirements of future devices and the intended dates for operation. The development phases for ST-40[14], ST-F1, and ST-E1 are aligned with the phases of innovation shown in the S-T-A-M model in Fig. 3, where "pre-cursor", "embryonic" and "nurture" were here defined for Tokamak Energy's mission as being; "research and development", "engineering demonstration" and "commercial roll-out" respectively. There is an explicit reference to the HTS magnet development programme as a critical enabling technology, as well as to TGI progression, and the intention for collaboration in the development programme. The overall appearance took inspiration from a range of previous roadmaps designed for communication, principally those by NASA but also from others referenced in (Phaal et al., 2010, Kerr and Phaal, 2015). "Spin-in" technologies, such as 3D printing, were included to signify Tokamak Energy's approach to capture external technology developments. Similarly, "spin-off" streams for technologies being developed in-house highlight other potential commercial opportunities, including HTS magnet development which has the potential to be a significant spin-off success. Together, these contribute to the overall aesthetic of the convergent-divergent structure, which was inspired by Chesbrough's open innovation funnel (Chesbrough, 2003). Here, all activities converge on ST-F1 as a focal point before diverging representing the numerous prospective commercial routes that have been identified outside of the primary goal of electricity generation.

This representation of the roadmap allows interested parties to quickly grasp the company's mission and thus assists inquiry into specific topics of interest, providing a bridge for discussions regarding all aspects of the programme. Alternative views of the roadmap could also be developed for instance to show the cost of individual TGI streams, to highlight IP opportunities that have been identified across TGI streams, or show the resources required to deliver specific programme elements.

7. Future roadmap development: introduction of a commercial market layer

Through the roadmapping process, commercial considerations have been incorporated into the roadmap developed for Tokamak Energy, but further consideration and integration of commercial drivers is possible. Methods and tools exist to support analysis of the commercial or "market" aspects, and these are commonly applied to support strategic management and for roadmapping. Three such methods are

[14] ST-40X is the extended operation of ST-40, which is a key test machine on the path to ST-F1.

PESTLE, SWOT and the innovation matrix.

PESTLE analysis assists the identification and understanding of the political, economic, social, technological, legal and environmental (hence "PESTLE") factors external to an organisation that may impact internal development (Newton and Bristoll, 2013). It has been used previously as a functional tool to support roadmapping in high technological ventures (see (Brenden et al., 2009)), and several elements of the method have already been incorporated in the roadmap developed for Tokamak Energy. To carry out the analysis, the possible influence of external factors on each element of the development programme (machines, projects, TGIs etc.) are identified and considered and, if appropriate, the development path adjusted to avoid potential problems or conflicts. For example, materials planned for the resolution of technical gap issues would be reviewed for their environmental acceptability and, if potential problems identified, alternatives would be sought. Similarly, the international transfer of specialist and potentially restricted use materials, such as tritium, requires compliance with specific legal and regulatory considerations (Pearson et al., 2018), and it would be beneficial to identify the requirement and take appropriate measures early. Of course, effective project management includes such preparations, but the PESTLE analysis formalises the process and brings the results and needed activities into the roadmap.

A method similar to PESTLE is SWOT, whereby strengths, weaknesses, opportunities and threats (hence "SWOT") in both the internal and external environment are explored and characterised (Pickton and Wright, 1998). SWOT analysis would likely be used at a system level rather than for specific technical gap issues. It is particularly useful for assessing markets and for evaluating competition. For example, it could be used to compare opportunities and challenges associated with developing an electricity-generating fusion power plant versus developing a fusion reactor for desalination; both of which have been identified as potential future applications for fusion technology (see Pearson, 2020). Both applications will serve a different market, both will involve different competitors, and both will likely involve different specifications for the technology to be developed. All of these factors may play to the strengths or weaknesses of the company's current technology capability. SWOT analysis could be used to characterise these, and to adjust the development plan towards desired applications.

Through the use of PESTLE and SWOT methods, content for an additional "market" or a "commercial" layer of the roadmap would be developed. Developing such a layer would require the involvement of management as well as advisors specialising in specific areas such as law and economics. An additional linkage grid would be added to characterise the links between the new layer and the existing layers of the roadmap. A tool specifically for this purpose is the innovation matrix, which is a strategic tool that was developed to identify and understand the links between technology uncertainty and the need for that technology, that is whether a technology will be "ready" to meet a required application (Groenveld, 1997, Matthews, 1991). In many ways, the innovation matrix is similar to a linkage grid, but the innovation matrix is deployed to identify innovation opportunities specifically. As such, it could be used to connect a "market" layer to the other layers of the roadmap. Once completed, the results of both analyses would be integrated into the roadmap.

8. Generalisability of the developed framework for other potential applications

All roadmapping processes are adapted to the needs of the organisation to which they are being applied. Despite efforts to create an objectively useful roadmapping framework by extracting the steps and lessons learned from the application to Tokamak Energy as a fusion start-up case study, the process was inherently tuned towards the company's needs and was guided by the company's management. Additional applications of the process would allow an assessment of its generalisability and would facilitate further development. Preferably those applications would be to other fusion start-ups. However, the process could also be usefully applied as a tool to support other missions from outside of the fusion sector that require similarly significant cost or time, and which involve the development of novel and complex hardware. In particular, the framework presented could be applied to missions that can be broadly categorised as problems that provide substantial societal benefit and that are world-changing. Such missions have a clear vision but typically work against substantial time pressure which requires ambitious but realistic cross-disciplinary R&D and innovation (Mazzucato, 2018). The framework presented can be used to guide innovation in such missions. Possible applications could be to support innovation and technology planning for "Generation IV" nuclear fission start-ups, or for missions to develop advanced low-carbon aircraft or biotechnology. Such missions all have high costs; similarly lengthy timescales from R&D to commercialisation; and multiple technical hurdles to overcome which presents substantial risk (see (Bowen, 2019, Singer and Bonvillian, 2017)). It may also be able to support X Prize Foundation missions, which are focused on enabling the realisation of disruptive technology to help deliver a better, safer and more sustainable world (see (Hossain and Kauranen, 2014)). An example of an existing X Prize mission is a call for the development of a technology to convert carbon emissions into useful products (see Carbon X Prize (Carbon X Prize Foundation Website: carbon.xprize.org 2019)). The roadmapping framework, as well as the characterised innovation approach, could be used to inform or guide sectors or even governments, as well as start-ups, for missions focused on agile hardware development.

9. Summary

The research presented in this paper comprehensively characterises the fusion start-up innovation system. Current programmes to develop fusion energy have been assessed in the context of innovation. The characteristics of the model of innovation – agile innovation – being pursued by recently emerging fusion start-ups, which are seeking a faster route to fusion, have been identified. Fusion start-ups are compared with government-funded fusion programmes which have, thus far, dominated fusion development. Public fusion programmes mostly follow a linear model of innovation, in which commercial aspects are not considered until later in development. We show that fusion start-ups are pursuing a fundamentally different route to the realisation of fusion energy in which longer-term commercial aspects influence the near and mid-term development programme. It is known from other technology fields that Technology Roadmapping is a useful tool to aid innovation. A method to develop a technology roadmap as a tool to support innovation in fusion start-ups has been developed. It has been applied to the development programme being pursued by Tokamak Energy Ltd, a privately funded company that is pursuing rapid development of commercial fusion via the spherical tokamak and high-temperature superconducting magnets. Our method has two key steps. First, it identifies the critical technical challenges that have to be overcome to achieve commercial fusion energy; it orders, characterises and prioritises the challenges; identifies and characterises links between them, and then identifies and develops potential methods of resolution. An initial roadmap is then drawn up and linked to the strategic goals of the company as well as the planned build-up of resources, such as workforce and facilities. In the second step, subject matter experts and appropriate company staff are involved, via dedicated review workshops and supported by focus workshops, in developing content which adds depth to the existing roadmap. A metric – technology readiness levels – can be used for judging progress on the technical elements towards commercialisation. The developed roadmap is then most appropriately updated at intervals aligned with agile build-measure-learn cycles and the development in relevant external factors.

At Tokamak Energy, in addition to its primary role assisting in the management and development of the technical programme, the roadmap has been used to manage uncertainty and risk through investigation of alternative candidate scenarios and thereby assisted in the selection of the most favoured path. It has also been used to communicate company plans to different audiences – potential investors, scientific journalists, researchers in related fields – by developing different representations of the roadmap. Further development and uses of the roadmap are possible through the application of tools, such as PESTLE and SWOT analyses. Potentially the developed roadmapping process could be applied to development programmes in similar fields; particularly for endeavours that involve technical uncertainty, significant cost or time, and require the development and integration of novel and complex technologies. Such applications have been briefly mentioned.

CRediT authorship contribution statement

R.J. Pearson: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **A.E. Costley:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **R. Phaal:** Conceptualization, Methodology, Resources, Writing - review & editing, Visualization, Supervision, Project administration. **W.J. Nuttall:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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